MEPAG

Special Regions – Science Analysis Group 2

Preliminary Report

Presentation to the NAC/PPS

May 13, 2014

J.D. Rummel for D.W. Beaty, M.A. Jones, and the SR-SAG2 Team

Preliminary results (see <http://mepag.jpl.nasa.gov> under Meetings, #29)

File Name: SR-SAG2_Compliation to PPS

COSPAR Definition: Special Regions on Mars

- A Special Region is defined as a region within which terrestrial organisms are likely to replicate.

- Any region which is interpreted to have a high potential for the existence of extant martian life forms is also defined as a Special Region
  - *Not the focus of SR-SAG2.*

SR-SAG 2 Primary Deliverables

(1a). Reconsider information on the known physical limits to life on Earth, particularly experimental results and environmental observations.

(1b). Evaluate new (i.e., since 2006) observational data sets and new models from Mars that could be relevant to our understanding of the natural variations on Mars of water activity and temperature.

(1c). Consider the observed and theoretical effects of mineral deliquescence on Mars and its potential biological availability.

(1d). Reconsider the parameters used to define the term "special region;" propose updates as warranted.

(2). Prepare an updated description in both text form, and as appropriate, in map form, of special and "uncertain" locations on Mars.

(3). To help guide future planning, prepare a preliminary analysis of the kinds and amounts of water-related resources on Mars of potential interest to the eventual human exploration of Mars, and evaluate the planetary protection implications of attempting to access/exploit them.

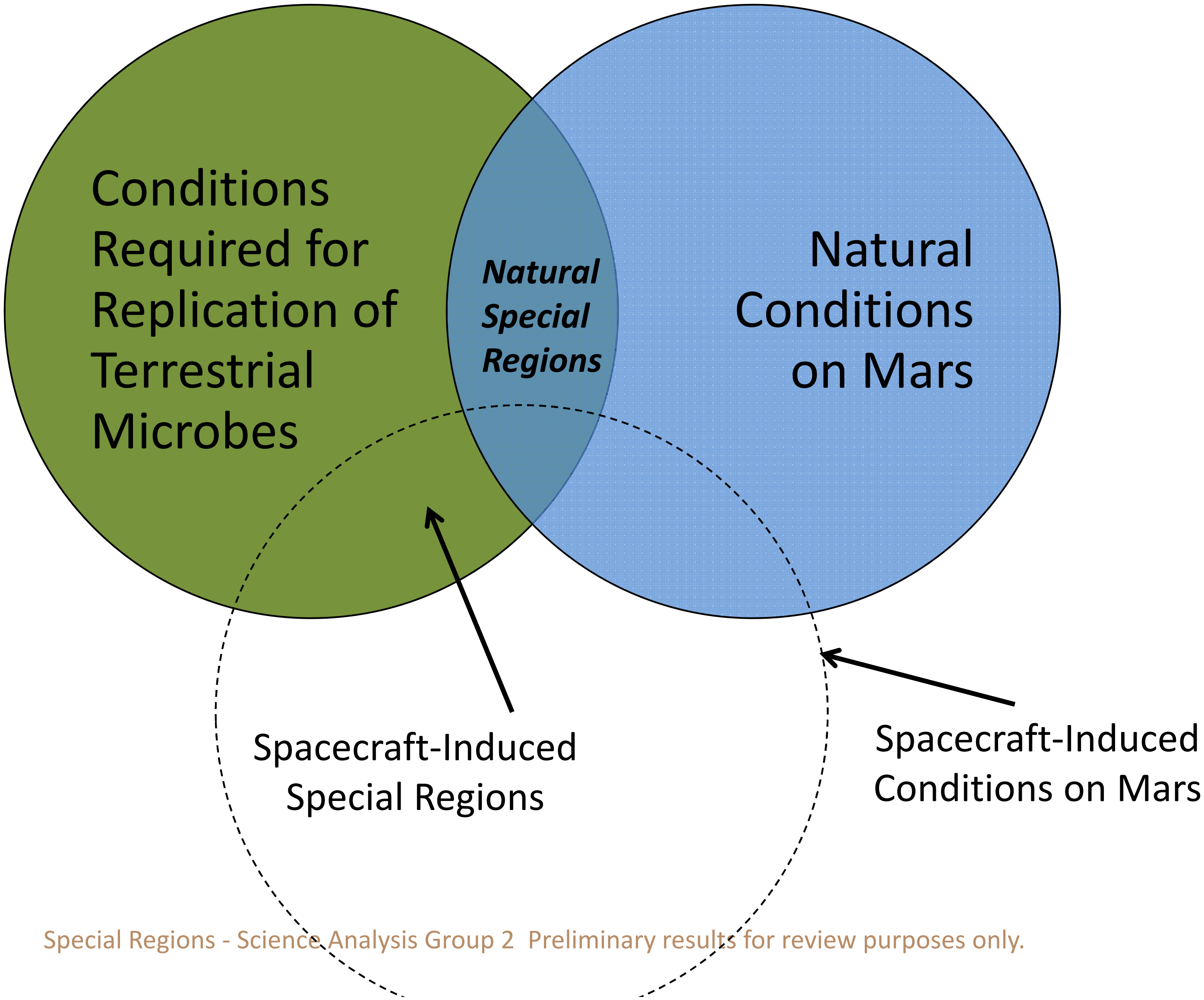
SR-SAG 2 Committee Members

Co-Chairs*/Technical Support			
Beaty*	Dave	Mars Program Office, JPL	Mars Chief Scientist
Rummel*	John	East Carolina Unversity	Chair, COSPAR Panel on Planetary Protection
Jones	Melissa	JPL	PP Group Supervisor, JPL
Members of the Science Community			
Bakermans	Corien	Penn State, Altoona	Microbiology, microbial survival, growth, metabolism at subzero temperatures
Barlow	Nadine	Northern Arizona University	Cratering on Mars
Boston	Penny	New Mexico Tech	Life in caves,cave geomicrobiology, microbial life in highly mineralized environments, unique or characteristic biominerals and biosignature detection
Chevrier	Vincent	University of Arkansas	thermodynamics, formation and stability of liquid brines
Clark	Ben	Space Science Institute	geochemistry, PP; Viking and MER
de Vera	Jean-Pierre	DLR Institute of Planetary Research	Astrobiology, Mars simulation, space experiments, polar research, life detection
Gough	Raina	University of Colorado	salt deliquescence; brine formation, stability and metastability
Hallsworth	John	Queen's University Belfast	Microbial-stress mechanisms & responses; solute activities of environmental & intracellular stressors; physicochemical limits of Earth's functional biosphere
Head	Jim	Brown	Mars ice, Antarctic analogs, linkages to human exploration
Hipkin	Vicky	Canadian Space Agency	Mars atmosphere, Phoenix
Kieft	Tom	New Mexico Tech	Microbiology of deep subsurface environments (deep drilling, deep mines)
McEwen	Alfred	University of Arizona	Mars surface geology, processes, MRO
Mellon	Mike	Southwest Research Institute	Ice on Mars, observed & modelled, PHX, MRO
Mikucki	Jill	University of Tennessee	Microbiology, Antarctica, microbiology of Subglacial environments
Nicholson	Wayne	University of Florida	Responses of terrestrial microbes to space and Mars environments (radiation, pressure, temp, atmospheric gases, etc.)
Omelon	Chris	University of Texas	Geomicrobiology, bacteria-mineral interactions; microbial biosignatures; polar and desert environments; cyanobacteria; electron microscopy; synchrotron radiation
Peterson	Ronald	Queen's University Canada	Mineralogy, deliquescence
Roden	Eric	University of Wisconsin	Microbial geochemistry, anaerobic geomicrobiology of sediments, soils, groundwater
Sherwood Lollar	Barbara	University of Toronto	Astrobiology, stable isotopes, biogeochemistry of deep subsurface hydrosphere; search for life
Tanaka	Ken	USGS Flagstaff	Planetary mapping, geologic history
Viola	Donna	University of Arizona	Distribution of water ice in/around Arcadia Planitia, ice/permafrost environments, graduate student (A. McEwen)
Wray	James	Georgia Tech	Mars surface geology, spectroscopy, MRO, MSL
Ex Officio			
Buxbaum	Karen	Mars Program Office, JPL	Mars Program Office PP Manager
Conley	Cassie	NASA HQ	NASA PPO
Kminek	Gerhard	ESA	ESA PPO
Meyer	Michael	NASA HQ	Mars Exploration Program Lead Scientist
Pugel	Betsy	NASA HQ	Detailee to NASA HQ for Planetary Protection
Voytek	Mary	NASA HQ	Senior Scientist for Astrobiology

SR-SAG 2 Committee Members

Not present for photograph: Barbara Sherwood Lollar, Ron Peterson, Jim Head, Betsy Pugel, Mary Voytek

The Concept of Mars Special Regions



Part 1. Known Environmental Limits to Life on Earth with Potential Application to Interpreting Special Regions on Mars

Chemolithoautotrophy and Mars

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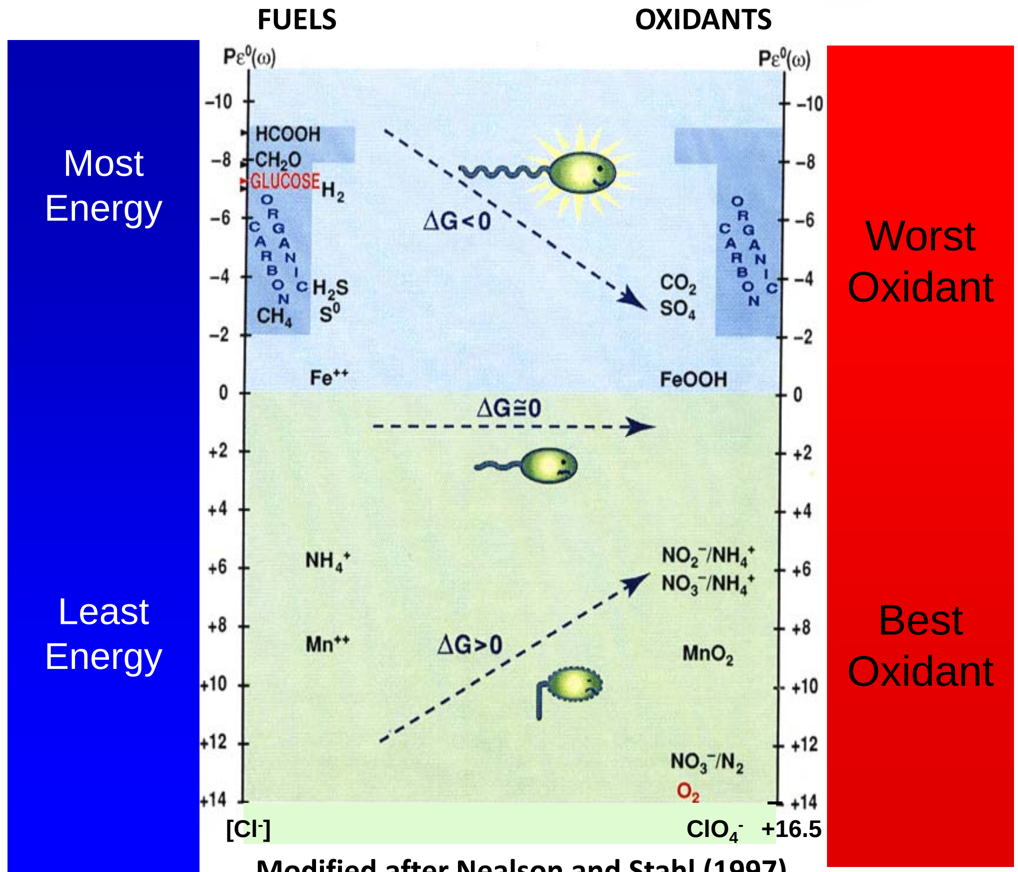
- Terrestrial microorganisms are well-known for their ability to grow autotrophically with inorganic energy sources
- Inorganic compounds such as reduced iron compounds in Martian rocks (e.g., ferrous silicates and sulfides) and fluids (e.g., dissolved ferrous iron in acidic groundwater), as well as H_2 and CO in the Martian atmosphere, could serve as energy sources for chemolithotrophic microbial metabolism in a special region
- O_2 is available in the Martian atmosphere at concentrations sufficient to permit growth of common organotrophic bacteria (see next slide), and could also potentially support aerobic chemolithotrophic metabolism
- Alternative oxidants such as nitrate, sulfate, dissolved ferric iron, ferric oxides, and ferric iron-bearing clays could be utilized by chemolithoautotrophs in the absence of O_2



Modified after Nealson and Stahl (1997)

Finding 1-1: Modern Mars environments contain a variety of fuels and oxidants that are known to support metabolism and cell division of chemolithoautotrophic Earth microbes on Earth.

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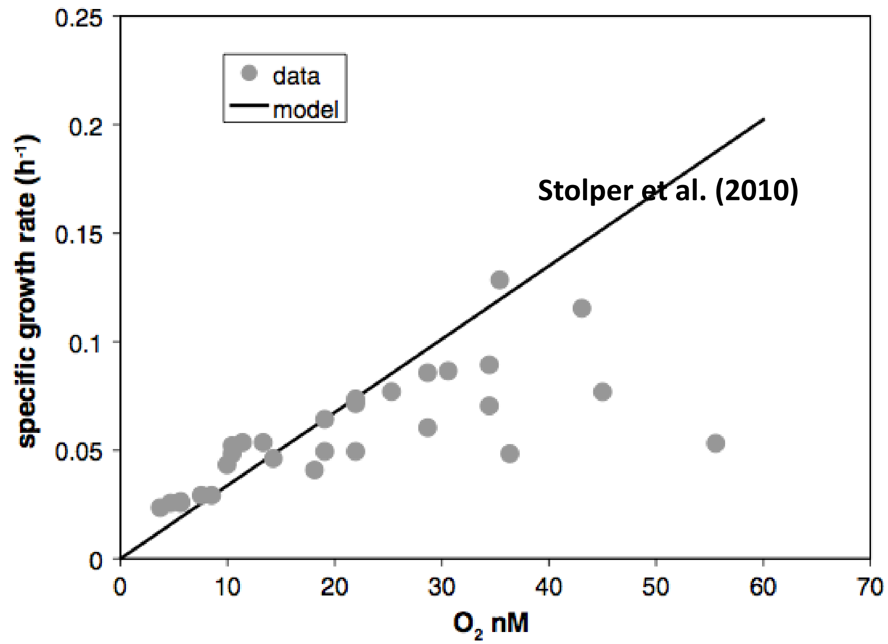
Oxygen on Mars

- Volume fraction of O_2 in the Martian atmosphere = 0.00145 (Mahaffy et al., Science, 2013)
- Equilibrium dissolved O_2 in water at total Mars atmospheric pressure of 5 mbar and 0^0C = 15.9 nM ($pO_2 = 10^{-5.14}$ atm)
- Experiments with polarographic STOX (Switchable Trace amount OXygen) sensors reveal that the common bacterium *Escherichia coli* can grow at 3 nM dissolved O_2 (Stolper et al. PNAS, 2010)
- Many Earth microorganisms contain high-affinity cytochrome oxidases analogous to those present in *E. coli* (Ducluzeau et al. Mol Biol. Evol., 2009)



Finding 1-2: The amount of O_2 found in the Martian atmosphere today has been shown to be sufficient to support the growth of some aerobic microorganisms on Earth.

Consideration of Microbial "Passenger Lists" for SR Planning

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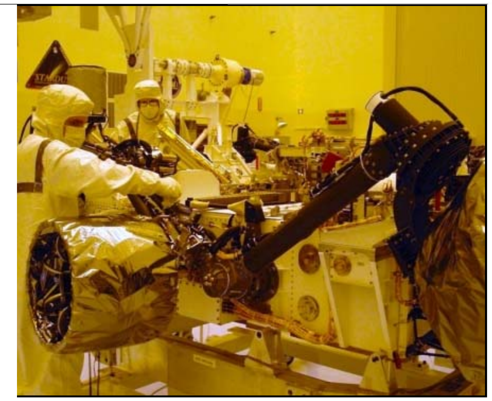
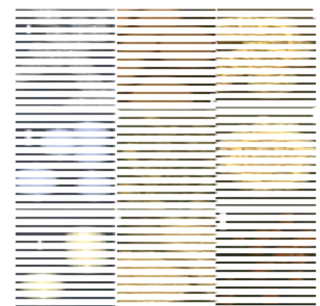
- If it were possible to perform a complete census of microbes on a spacecraft (or spacecraft in general), then analysis for SR planning could conceivably be narrowed to consider only organisms in the census and their survival limits.
- However, it is impractical (probably impossible) to identify and characterize all of the microbes on and within any given spacecraft.
- Furthermore, numerous spacecraft diversity studies indicate that there is significant (and variable) diversity of potential hitchhikers.
- Current (inherently incomplete) surveys of potential microbial passengers on Mars-bound spacecraft include a variety of taxa with hardy survival and reproductive capabilities.
- Therefore, it is reasonable and prudent to use an inclusive approach, searching all peer reviewed scientific literature for examples of Earth organisms shown to function and reproduce at extremely low temperatures or water activity.
- Microbial passenger lists will help to better evaluate/identify organisms we find through "life detection" experiments on Mars, or when we get a sample back.



Sample collection from MSL rover before launch



Microbes collected from spacecraft and associated environments

Finding 1-4: There is no evidence that any terrestrial microbial taxon can be ruled out as a potential "passenger" on spacecraft.
Finding 1-5: Notwithstanding extensive spacecraft biodiversity studies, it is reasonable for this analysis to use knowledge drawn from all biological organisms, not a subset or "passenger list."

Recommended Parameters to Use in Identifying Special Regions

No change since SR-SAG1

Parameter	Recommended for inclusion in identifying Special Regions?	Comment
Temperature	**Yes**	Same as in 2006.
Water activity	**Yes**	Same as in 2006.
Nutrient limitation	**No**	To date, direct *in situ* experiments have failed to detect significant amounts of organic compounds in regolith.
Ultraviolet radiation	**No**	New published results do not indicate changes in the 2006 conclusion: unshielded spores are rapidly inactivated but thin layers of shielding could protect microbes.
Ionizing radiation	**No**	Ionizing radiation flux is too low to exert a biocidal effect on microorganisms over 500 years.
Chaotropic compounds	**No**	Numerous chaotropic salts have been identified on Mars including LiCl, FeCl, MgCl2, FeCl2, CaCl2, FeCl3, and perchlorate salts. If present in aqueous milieu that can act as potential microbial habitats, these salts may be present over a range of concentrations (up to saturation). Were microbial cells present at such locations, chaotropic substances would enhance flexibility of their macromolecular systems. It has not yet been determined whether this would be sufficient to enable cell division at martian temperatures of less than -18°C.
Atmospheric composition	**No**	The Mars atmosphere is intrinsically a global environment and affects all locations similarly. Active hydrothermal vents, such as fumaroles, have not been detected on Mars.
Atmospheric pressure	**No**	Examples of terrestrial microbes have been found to reproduce at simulated Mars atmospheric pressure.
Vapor phase water	**No**	Literature review does not show definitive evidence that any terrestiral organism can utilize ambient humidity alone to achieve cell reproduction.
Liquid water from mineral deliquescence	**No**	Brines formed by deliquescence are inferred to be stable under natural Mars conditions in at least some locations and for at least some periods of time, but are not within the temperature and water activity Special Regions boundary conditions.
Thin film water	**No**	Microbial growth in unsaturated soil has not been measured below $a_w = 0.89$. Matric-induced (desiccation) reductions in water activity are more inhibitory to microbial growth than solute-induced reductions in water activity.

Low-Temperature Limit for Terrestrial Life

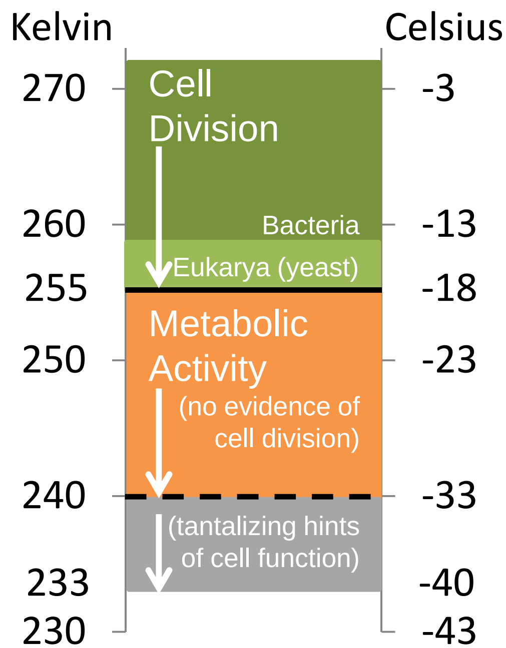
T (°C)	Activity	Method	Environment	Time-scale (days)	Reference
Brines					
-10	Cell division DT 39 days	Plate counts, turbidity measurement	Culture of permafrost isolate *Psychrobacter cryohalolentis* in brine (10% NaCl)	60	(Bakermans et al., 2003)
-12	Cell division DT 10 days	Turbidity measurement	Culture of sea ice isolate *Psychromonas ingrahamii* in brine (5% glycerol)	42	(Breezee et al., 2004)
-13.5	Protein synthesis	Uptake of ^{3}H-leucine	Lake Vida samples (188 psu salinity, primarily Cl^-, Na^+, Mg^{2+})	6-30	(Murray et al., 2012)
-15	Cell division DT 50 days	Plate counts	Culture of permafrost isolate *Planococcus halocryophilus* Or1 in brine (18% NaCl, 7% glycerol)	200?	(Mykytczuk et al., 2013)
Ices and Frozen environments					
-5	Respiration (maybe cell division, DT 43 days)	CTC reduction, cell numbers, respiration of ^{14}C-acetate, incorporation of ^{3}H-adenine, ^{3}H-leucine	Frozen cultures of glacial ice isolate *Paenisporoarcina* sp. and *Chryseobacterium*	50	(Bakermans and Skidmore, 2011a)
-10	CH_4 production	Reduction of $H^{14}CO_3^-$	Arctic permafrost	21	(Rivkina et al., 2007)
-15	DNA/Protein synthesis	Uptake of ^{3}H-thymidine and ^{3}H-leucine	Frozen cultures of glacial ice isolates *Psychrobacter* sp. and *Arthrobacter* sp.	50	(Christner, 2002)
-15	Metabolism	Incorporation of ^{14}C-glucose	Arctic permafrost	1	(Gilichinsky et al., 2003)
-18	Metabolism	Incorporation of $^{14}CO_2$	Frozen cultures of permafrost isolates	90	(Panikov and Sizova, 2007)
-18	Cell division	Plate counts	*Rhodotorula glutinis* (a yeast) inoculated onto surface of frozen peas	200	(Collins and Buick, 1989)
-20	Metabolism	Incorporation of ^{14}C-acetate into lipids	Permafrost microcosms	550	(Rivkina et al., 2000)
-20	Respiration	CTC reduction	Sea ice	1	(Junge et al., 2004)
-20	Protein synthesis	Uptake of ^{3}H-leucine	Frozen culture of sea ice isolate *Colwellia psychroerythraea* 34H	6	(Junge et al., 2006)
-15, -33	Respiration	CTC reduction, respiration of ^{14}C-acetate	Frozen cultures of glacial ice isolates *Paenisporoarcina* sp. and *Chryseobacterium*	200	(Bakermans and Skidmore, 2011b)
-25	Respiration	Mineralization of ^{14}C-acetate to $^{14}CO_2$	Permafrost microcosms w/ *Planococcus halocryophilus* Or1 added	200	(Mykytczuk et al., 2013)
-32	Ammonia oxidation	$^{15}N_2O$ production from ^{15}N-ammonia	Frozen culture of marine isolate *Nitrosomonas cryotolerans*	307	(Miteva et al., 2007)
-15 to -40	Photo-synthesis?	Fluorescence of chlorophyll a in photosystem II	Thalli of the lichen *Pleopsidium chlorophanum* collected from Antarctica and incubated in Mars simulation chamber	35	(de Vera et al., 2014)

- Studies highlighted in gray were included in the 2006 SR-SAG report
- New data on yeast extend the lower temperature record for cell division to -18°C
- Metabolism is known to extend to temperatures lower than the limit for cell division
  - Cell division is the foundation for Special Regions planning
- Laboratory experiments on replication at these low temperatures are difficult and can take a very long time
  - Leads to intrinsic uncertainty in measuring the lower limit

Low-Temperature Limit for Terrestrial Life

- Literature found since the 2006 report has shown evidence of cell division at -18°C, extending the low temperature from -15°C.

Temperature Limits
of Metabolic Activity
in Terrestrial Microbes



Finding 1-6: Cell division has not been reported below -18˚C (255K).
Finding 1-7: Cellular metabolic activity has not been demonstrated below -33˚C (240K), although some biophysical processes may be functional at lower temperatures.

Some Compounds Can Decrease the Low-Temperature Limit of Growth

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- The structural integrity and functionality of cellular systems depend on macromolecular flexibility as well as stability.
- Low temperatures increase stability and rigidity, thus metabolism can only continue if the flexibility of molecules is maintained.
- Some compounds increase the flexibility of molecules, destabilizing and/or fluidizing them, and are known as chaotropic compounds or chaotropes.
- Chaotropes have been shown to decrease the lower temperature limit of growth of microorganisms (Cray *et al.,* 2013; Chin *et al.,* 2010).
- Chaotropic compounds on Mars include $MgCl_2$, $CaCl_2$, $FeCl_3$, $FeCl_2$, FeCl, LiCl, perchlorate, and perchlorate salts.

Effect of chaotropes on growth of psychrophilic yeast *Mrakia frigida*

Compound	Chaotropic activity (kJ kg-1)	Temperature limit of cell division (°C)	
		Usual	Modified
$MgCl_2$ (1 M)	54.0	≈1	<-5
Glycerol (1.1 M)	1.17	≈1	<-5
Methanol (1.26 M)	4.87	≈1	<-5

Finding 1-8: Chaotropic compounds can lower the temperature limit for cell division below that observed in their absence. The possibility that chaotropic substances may decrease the lower temperature limit for cell division of some microbes to below -18°C has not yet been tested.

Low Water Activity Limit for Terrestrial Life

No change since SR-SAG1

Water Activity	Microorganism		
	Bacteria	Molds	Yeast
0.97	*Clostridium botulinum E*		
	Pseudomonas fluorescens		
0.95	*Escherichia coli*		
	Clostridium perfringens		
	Salmonella spp.		
	Vibrio cholerae		
0.94	*Clostridium botulinum A, B*	*Stachybotrys atra*	
	Vibrio parahaemolyticus		
0.93	*Bacillus cereus*	*Rhizopus nigricans*	
0.92	*Listeria monocytogenes*		
0.91	*Bacillus subtilis*		
0.90	*Staphylococcus aureus (anaerobic)*	*Trichothecium roseum*	*Saccharomyces cerevisiae*
0.88			*Candida*
0.86	*Staphylococcus aureus (aerobic)*		
0.85		*Aspergillus clavatus*	
0.84		*Byssochlamys nivea*	
0.83		*Penicillium expansum*	*Debarymoces hansenii*
		Penicillum islandicum	
		Penicillum viridicatum	
0.82		*Aspergillus fumigatus*	
		Aspergillus parasiticus	
0.81		*Penicillium cyclopium*	
		Penicillum patulum	
0.80		*Penicillium citrinum*	*Saccharomyces bailii*
0.79		*Penicillium martensii*	
0.78		*Aspergillus flavus*	
0.77		*Aspergillus niger*	
		Aspergillus ochraceous	
0.75		*Aspergillus restrictus*	
		Aspergillus candidus	
0.71		*Eurotium chevalieri*	
0.70		*Eurotium amstelodami*	
0.62			*Saccharomyces rouxii*
0.61		*Monascus bisporus*	
<0.60	*No microbial cell division*		

(Fontana, 2007, Water Activity in Foods: Fundamentals and Applications)

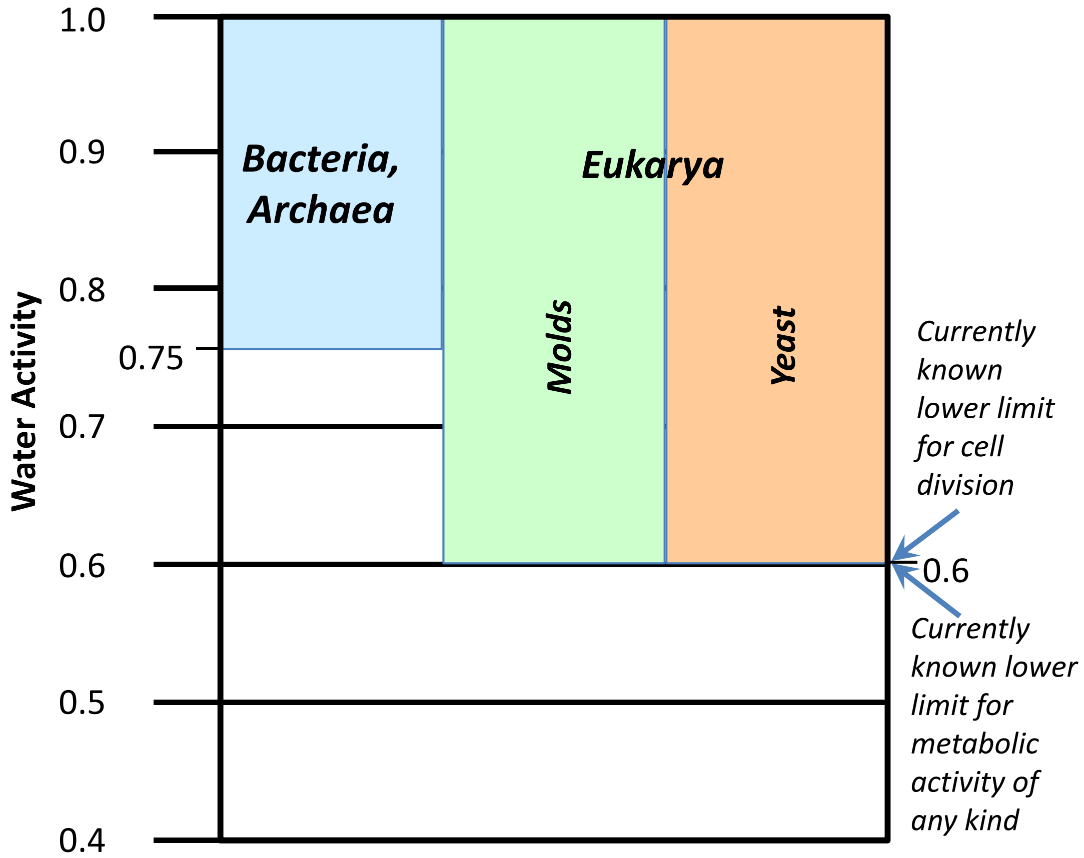
Lowest known water activity for cell proliferation:
Spore germination in filamentous fungus *Monascus bisporus* at a_w = 0.605 (Pitt and Christian, 1968).
This is in a sucrose solution – relevant to food, but not Mars.

Salt solutions are more relevant to Mars.
Many bacteria, archaea, and eukarya grow in saturated NaCl (a_w = 0.75). This is the lower limit growth in salt solutions. Other salts (e.g., $MgCl_2$, $MgSO_4$) are more toxic that NaCl.

Finding 1-9: Review of the literature since the previous SR-SAG report (2006) shows no evidence of either cell division or metabolism below a_w of 0.6.

Low Water Activity Limit for Terrestrial Life

No change since SR-SAG1



Finding 1-9: Review of the literature since the previous SR-SAG report (2006) shows no evidence of either cell division or metabolism below a_w of 0.6.

Mars Atmospheric Composition and Pressure

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- Most bacteria, including laboratory strains, Spacecraft Assembly Facility isolates, and environmental isolates, cannot reproduce below 25 mbar. However, this growth inhibition is not lethal, and cell division resumes immediately upon return to Earth pressure (numerous references).
- A small number of bacteria have been found that can grow under simulated "Mars" atmospheric conditions: anoxic, CO_2; 7 mbar; 0˚C (30 day experiment shown in figure below).
- But, experiments were performed on rich, hydrated agar medium.

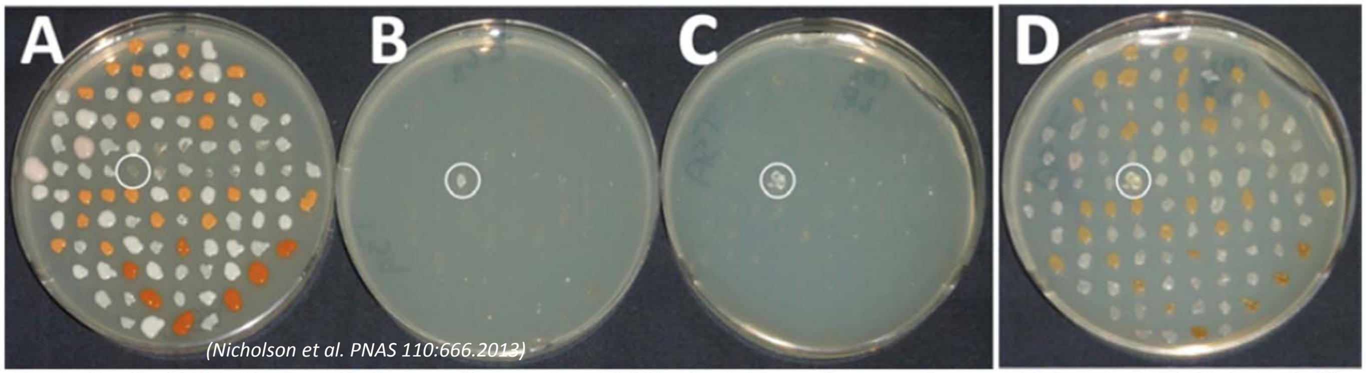


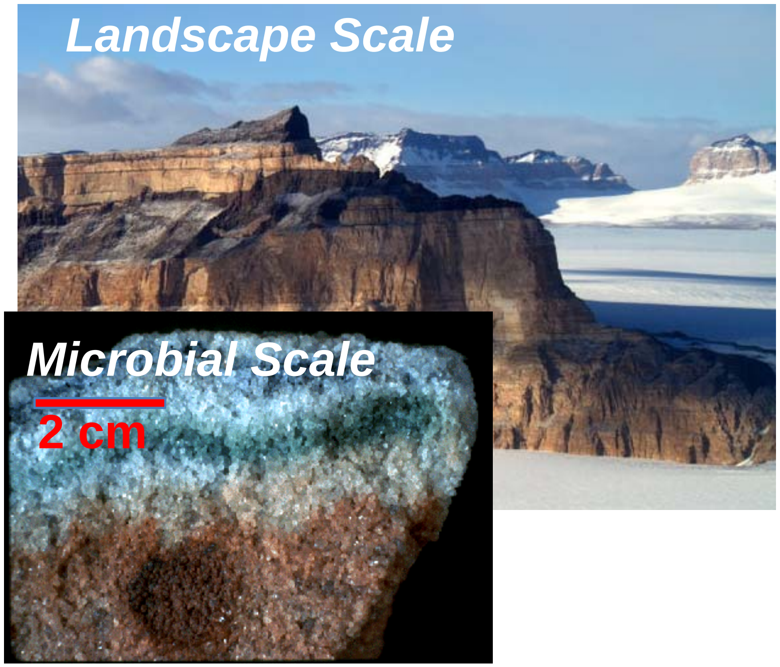
Fig. 2. Growth of 100 isolates from Siberian permafrost samples on TSBYS plates. Isolates are from permafrost sample 5 (colonies 1–25), 4 (colonies 26–50), 8 (colonies 51–75), and 9 (colonies 76–100). (*A–C*) All isolates were cultivated for 30 d at 0 °C under the following conditions: (*A*) Earth atmosphere and pressure. (*B*) Simulated Mars atmosphere, Earth pressure. (*C*) Simulated Mars atmosphere and pressure. Colony 43 from permafrost sample 4 was designated strain WN1359. (*D*) Same plate as in *C*, but after 1 additional day of incubation on the laboratory bench (i.e., at room temperature, Earth atmospheric composition and pressure).

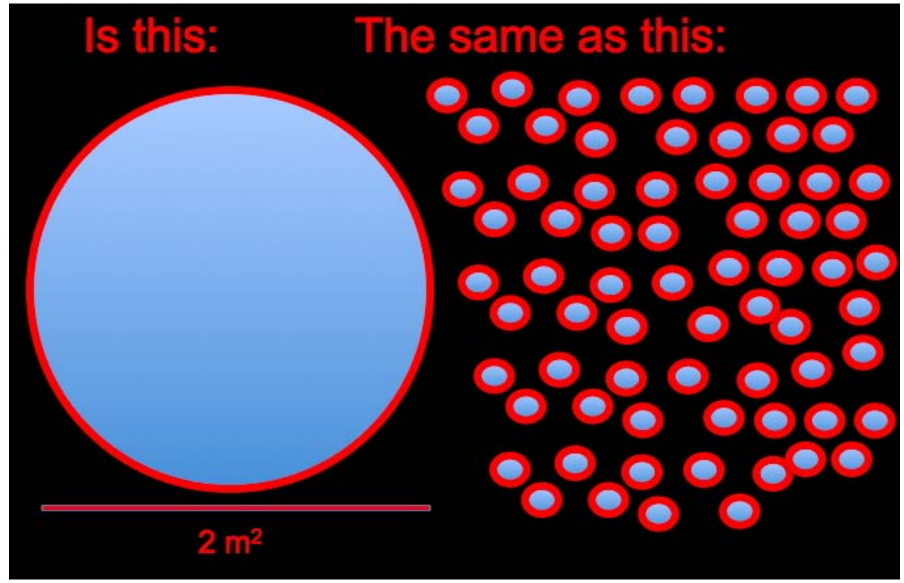
Finding 1-12: Most Earth bacteria tested fail to grow below 25 mbar. However, a small subset of bacteria have now been identified that can reproduce in a "Mars" atmosphere (anoxic, CO_2) at average Mars pressure (7 mbar) and 0˚C *on rich hydrated agar media.*

SR – SAG 2

Part 2. Issues involving microbial microenvironments that we know exist on Earth, and that may be relevant on Mars—scale and timing

Problems of Scale





- Large-scale environmental conditions discernable from orbit, and their changes with time, cannot be assumed to be identical to the conditions felt by organisms at the microscopic level.

Finding 1-13: Determining the continuity/heterogeneity of micro-scale conditions over time and space is a major challenge.

Bridging the Gap Between Orbital Data and Microbiology

Mars Example: The PHX landing site observed at different scales

	Scale	Data	Similarity required	Key missing data
Orbital scale	Latitude band 65-72N	GRS hydrogen in top 1m, polygonal terrain, boulder maps, thermal inertia at 2-4pm	Similarity of ice, geology and polygonal terrain is observed across latitude band: detailed data collected for 4 large regions	Chlorine maps – GRS chlorine too noisy in presence of high hydrogen at high latitude
Lander scale	Phoenix site	Diurnal surface/air/soil temperature; near surface humidity, fog, cloud, snow	Polygon is representative of polygonal terrain. T and A_w should be successfully modeled across Latitude band; similarity should be demonstrated at analogue site.	Arm in shadow at midday; local control of humidity by soil, low cloud, snow not currently modeled; Dry Valley temperatures inevitably higher than Mars, snowmelt occurs
	Phoenix trench samples	Soil and ice layer sampled, perchlorate, wet chemistry and clay particles detected	Depth layers should be successfully modeled across polygon; similarity demonstrated at analogue site?	Mechanism of observed ice distribution is not understood
Micro scale	Analogue trench samples	Detailed redox profile acquired	Similarity to Phoenix is somewhat demonstrated in constituent composition and distribution: perchlorate and wet chemistry	Alternative mechanisms may work on Mars, and other mechanisms at analogue site may obscure Mars processes
	Microscale	Microbiology associated with redox profile analyzed	Understood history of analogue; past mechanisms may still leave imprint on current status of habitats	Past history and "real-time" microbial abundance and essential adaptations

Microenvironments of Known Relevance to Terrestrial Microbes

Some Highlights in slides 22-26

Potential habitat on Mars for a microbe from Earth		Description
Naturally Occurring Microenvironments		
A	***Vapor phase water available***	Vapor or aerosols in: planet's atmosphere; within soil cavities, porous rocks, etc; within or beneath spacecraft or spacecraft debris
B	***Ice-related***	Liquid or vapor-phase water coming off: frost; solid ice; regolith or subsurface ice crystals; glaciers
C	***Brine-related***	Liquid water in: deliquescing salts; channels within ice; on the surface of ice; within salt crystals within halite or other types of 'rock salt'
D	***Aqueous films on rock or soil grains***	Liquid water on: regolith particles of their components such as clay minerals; surface of ice; on and within rocks; surfaces of spacecraft
E	***Groundwater & Thermal springs (macroenvironments)***	Liquid water
F	***Places receiving periodic condensation or dew***	Liquid water on: regolith particles of their components such as clay minerals; surface of ice; on and within rocks; surfaces of spacecraft
G	***Water in minerals***	Liquid water bound to minerals
Exploration-Induced Microenvironments		
H	***Microbial material***	Vapor or liquid water: captured by a cell's own cell wall or absorbed due to hygroscopic nature of cellular metabolites; obtained from microbial necromass
I	***Astronauts***	In various forms (including generation of water via microbial metabolism) from: skin; dead skin; human hair; human waste; and microbes from gut microflora or respiratory surfaces including the lungs
J	***Organic material released in a collision***	In various forms (including generation of water via microbial metabolism) from: food; human; stored wastes; etc
K	***Melt water with a perennial heat source***	Radioisotope components can melt subsurface ice on Mars, leading to liquid water microenvironments that can be stable for more than a martian year

Limits on Microbial Use of Vapor Phase Water

% RH	Microorganism(s)	Method	Author
80	Lichens in hot deserts	CO_2 gas exchange	Lange (1969)
80	Negev Desert lichens	CO_2 gas exchange	Lange et al (1970)
96.2	*P. maydis* conida incubated on glass slides	--	Bootsma et al (1973)
> 97	*Chroococcidiopsis* sp. from Negev Desert	$^{14}CO_2$ incorporation	Potts and Friedmann (1981)
97	Numerous lichens with algal phytobionts; cyanobacterial phytobionts required liquid water	CO_2 gas exchange	Lange et al (1986)
70	*Dendrographa minor*	CO_2 gas exchange	Nash et al (1990)
70	Antarctic cryptoendolithic lichen	$^{14}CO_2$ incorporation	Palmer and Friedmann (1990)
> 90	Negev Desert *Chroococcidiopsis* sp.	$^{14}CO_2$ incorporation	Palmer and Friedmann (1990)
> 80	*Ramalina maciformis* and *Teloschistes lacunosus*	$^{14}CO_2$ incorporation	Palmer and Friedmann (1990)
96	*Microcoleus sociatus* isolated from biological soil crusts from Negev Desert	CO_2 gas exchange	Lange et al (1994)
94 for alga photobiont	*Placopsis contortuplicata* (lichen)	Chlorophyll a fluorescence measurements	Schroeter (1994)
??	*Umbilicaria aprina* at Granite Harbor, Antarctica; net productivity lowered at -3˚C due to dehydration by ice formation in thallus (atmospheric humidity equilibrium)	CO_2 gas exchange	Schroeter et al (1994)
??	*Umbilicaria aprina* under snow cover; water uptake in gaseous phase; increased humidity due to equilibrium with snow	CO_2 gas exchange	Schroeter and Scheidegger (1995); Pannewitz et al (2003)
82	*Teloschistes capensis* from central Namib Desert; integrated daily carbon income requires fog or dew	CO_2 gas exchange	Lange et al (2006)
Inactive at > 90%; dew required	*Teloschistes lacunosus* (lichen) in Tabernas Desert (Spain)	Chlorophyll a fluorescence measurements	del Prado et al (2007)
80.6 (1 bar) 82.7 (0.5 bar)	*S. epidermis*	Environmental control chamber	de Goffau et al (2011)
91.6 (1 bar) 92.9 (0.5 bar)	*B. subtilis*	Environmental control chamber	de Goffau et al (2011)

Limits on Microbial Use of Vapor Phase Water

Finding 1-14: Review of the literature suggests that metabolism (net photosynthesis) by lichens using water vapor alone can occur at an RH as low as ~70%, specifically with algal photobionts. Cyanobacterial photobionts require liquid water for metabolism. Reasons why these differ remain poorly understood.

Finding 1-15: We have not found definitive evidence that any terrestrial organism can utilize ambient humidity alone to achieve cell reproduction. In experiments to date, liquid water is needed at some point in the life cycle of the organism.

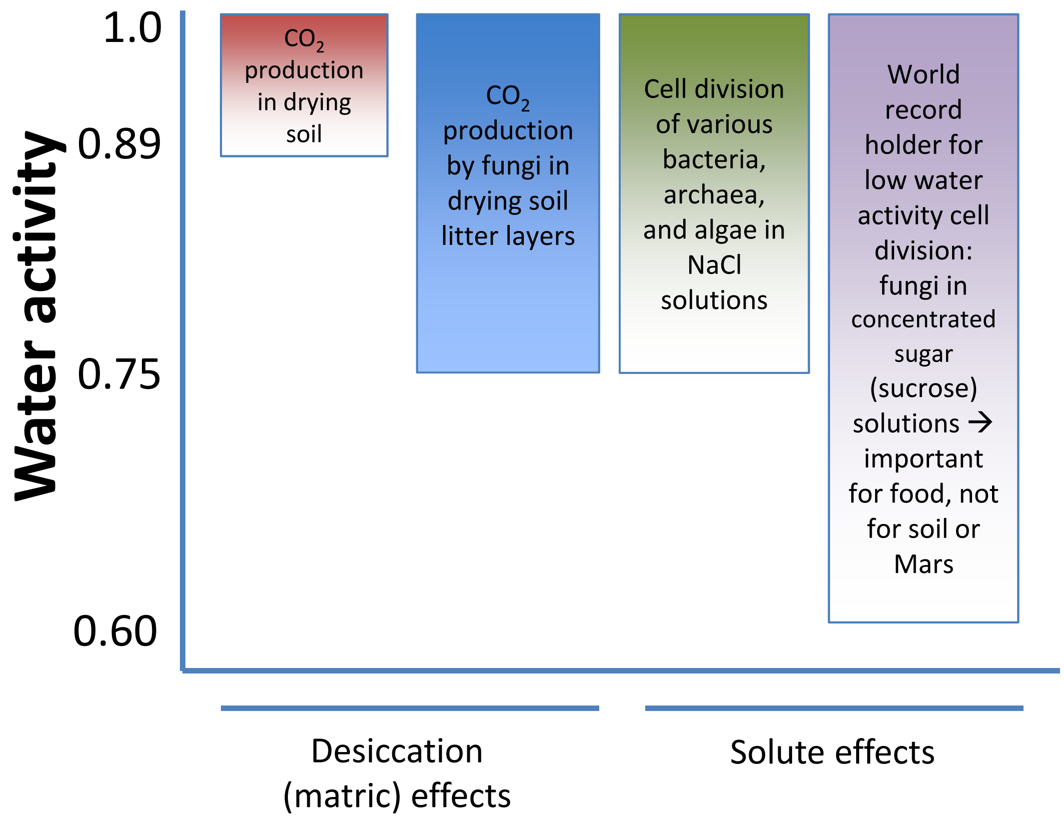
- Since the driving requirement for the identification of Special Regions is the capability for cell division, this means that the presence and concentration of vapor phase water by itself has not been shown to create a Special Region.
- However, as discussed elsewhere, brines that may be habitable by terrestrial organisms can be in equilibrium with vapor with an RH of 0.7, so readings this high can be an indirect indication of "Special" conditions nearby.
- In addition, condensation of vapor phase water in microenvironments may create environments amenable to microbial colonization.

D

Limits Related to Matric-Induced Reduction of Water Activity Alone (Desiccation in a Porous Medium)

- Microbial cell division in unsaturated soil has not been measured below $a_w = 0.89$.
- This matric-induced a_w corresponds to an average thin film thickness of ~10 nm (less than 1/20th the diameter of the smallest cells).
- Solute diffusion in such thin water films does not support microbial cell division.
- Filamentous fungi show activity (but not cell division) down to 0.75.

Water activity limits to terrestrial life



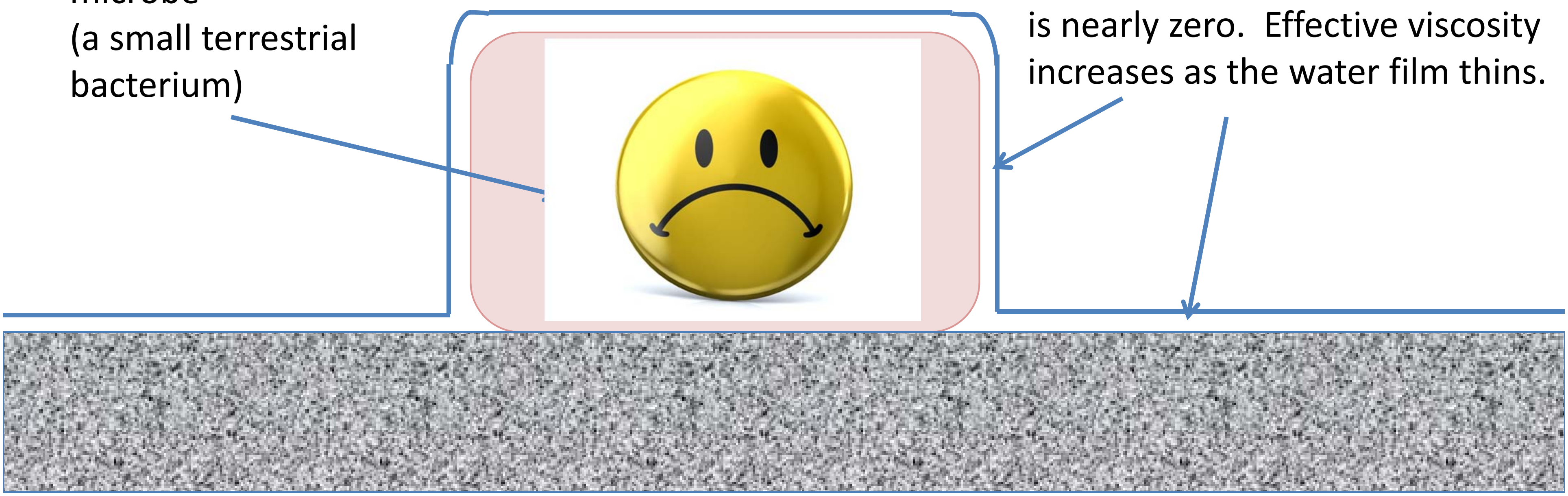
Finding 1-16: Matric-induced (desiccation) reductions in water activity are more inhibitory to microbial cell division than solute-induced reductions in water activity.

Microbial Cell at a_w = 0.89 (Schematic)

Microbial cell on a solid surface in an unsaturated porous medium (soil, food, martian regolith, etc.) at a_w = 0.89

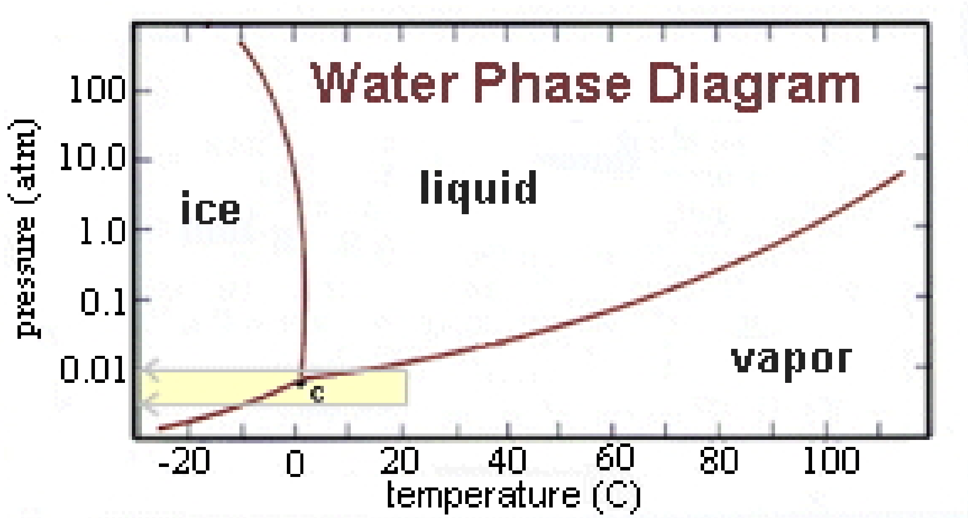
200 nm diameter microbe
(a small terrestrial bacterium)

Thin water film, ~10 nm thick at A_w = 0.89. Diffusivity in the film is nearly zero. Effective viscosity increases as the water film thins.



Finding 1-17: Thin films on grains in the shallow subsurface are not interpreted to be habitable by terrestrial microbes under environmental conditions currently on Mars.

Condensation



Finding 1-18: Mars conditions are very close to the triple point of water, and temporary excursions of temperature and pressure may allow condensation over limited times/areas

- Condensation of vapor phase water in microenvironments can conceivably create liquids that organisms can use directly, or even result in environments amenable to microbial colonization.
  - Frosts are water vapor deposited on cold surfaces, and are easily sublimated without entering liquid phase (below the box).
  - Nucleation of water in the upper atmosphere (snow) can result in a local disequilibrium by falling onto the surface, and melting can occur before boiling
  - Nucleation of water vapor in clays, and in specialized organs (lichen thalli) may also occur

Part 3. Mars Environments and Possible Naturally Occurring Special Regions

Features evaluated in this section:

Geomorphic Feature	Why evaluated?
RSLs	New discovery since 2006
Pristine gullies	Significant new understanding
Slope streaks	Significant new understanding
Polar dark dune streaks	Significant new understanding
Recent craters that are still warm	Greatly improved crater database
Deep groundwater	New data from MARSIS, SHARAD
Thermal zones	New data from THEMIS
Caves	Not previously considered

Context and Forecast for the 500 Year Protection Period on Mars

CONTEXT OF THE 500-YEAR PERIOD

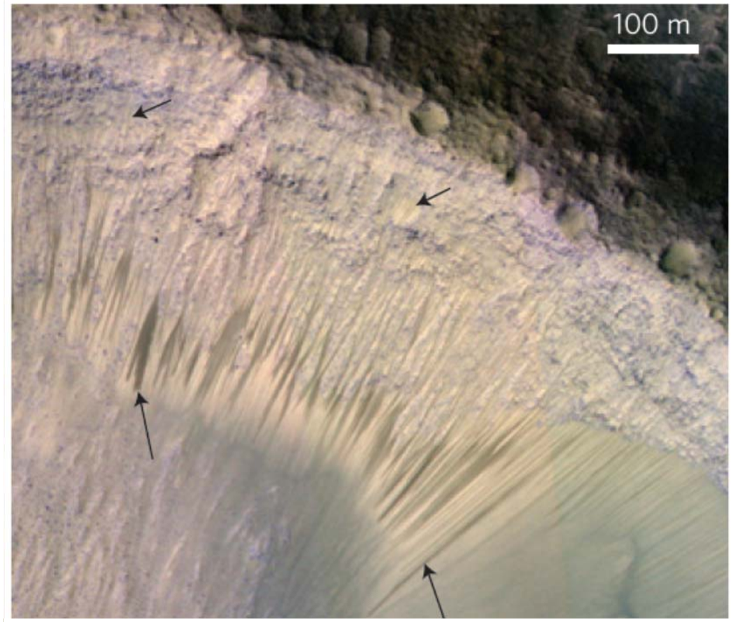
- A recent ice age occurred on Mars from about 2.1 to 0.4 Ma due to the obliquity shifting to 30–35°.
- This ice age drove significant ice from the poles symmetrically down to latitudes of ~30° across all of Mars, and locally all the way to the equator.
- Mars is currently in an inter-glacial period during which the recent glacial deposits are in retreat, as the low- and mid- latitudes warm up and dry out, and the water moves towards the poles.
- The 500-year interval of PP protection will entirely lie within the current inter-glacial period.

500-YEAR FUTURE FORECAST

- On the scale of 500 years, the biggest change in Mars' orbit will be a small precession of the perihelion. This has a period of 50k years, so in 500 years Ls will increase by a few degrees.
- The eccentricity and obliquity are also increasing slowly--in 500 years the change will be <<1%.
- The effect on ground temperatures will be rather small – estimate is <0.1K, smaller than the uncertainty.
- There will be negligible predicted change to the atmospheric water cycle.
- **Overall**: Low latitudes will continue to dry out slowly, with water moving to the high latitudes.

Recurring Slope Lineae (RSL)

- Recurring slope lineae (RSL) are narrow (0.5-5 m), abundant (>10), recurring dark markings on steep slopes (>25°).
- They are concentrated in southern hemisphere (32°S to 48°S), favoring equator-facing slopes, form and incrementally grow in late spring to summer, then fade or disappear in fall.
- They are also found in Valles Marineris on sun-facing slopes.
- They recur at nearly same locations in multiple Mars years.
- Extend downslope from bedrock outcrops or rocky areas; often associated with small gullies.
- RSL active in seasons when peak temperatures > 250 K in THEMIS. (Actual peak surface temperatures likely higher.)



RSL location in this image is Melas Chasma (McEwen et al, 2013).

Additional details on RSL in Appendix I

Recurring Slope Lineae (RSL) Findings

Finding 2-2: RSL are currently best explained by the seepage of water at >250 K, with a_w unknown and perhaps variable.

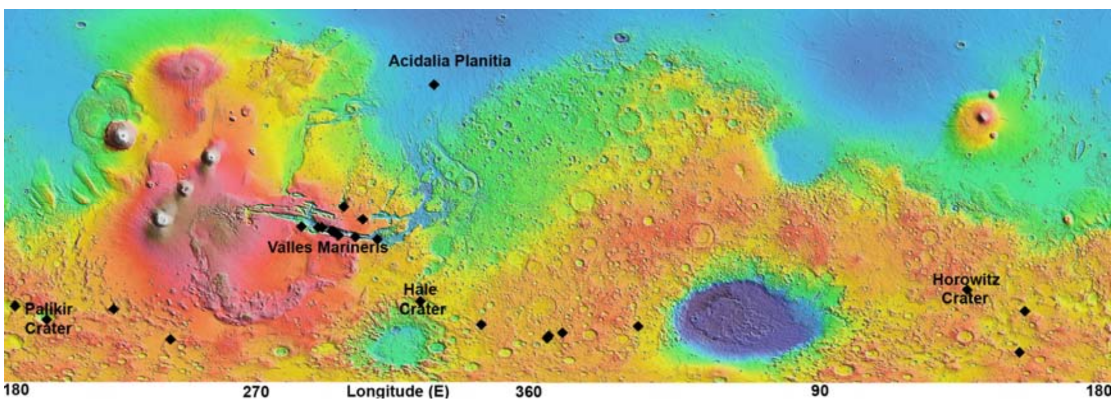
- Leads to recommendation that they should be treated as Special Regions.
- Soft landing ellipses will not include the steep slopes where RSL are found, but a rover could drive to such slopes and probes or other experiments could reach these sites.

Finding 2-3: High-resolution monitoring was required to confirm the presence of RSL.

- Many slope lineae look alike, temporal information is essential to identify RSL.

Finding 2-4: There are other features that have similar characteristics to RSL perhaps involving water but their characteristics are not identical.

- Example: in Aram Chaos, slope lineae only grow a bit at their tips and have not faded over 2 Mars years.



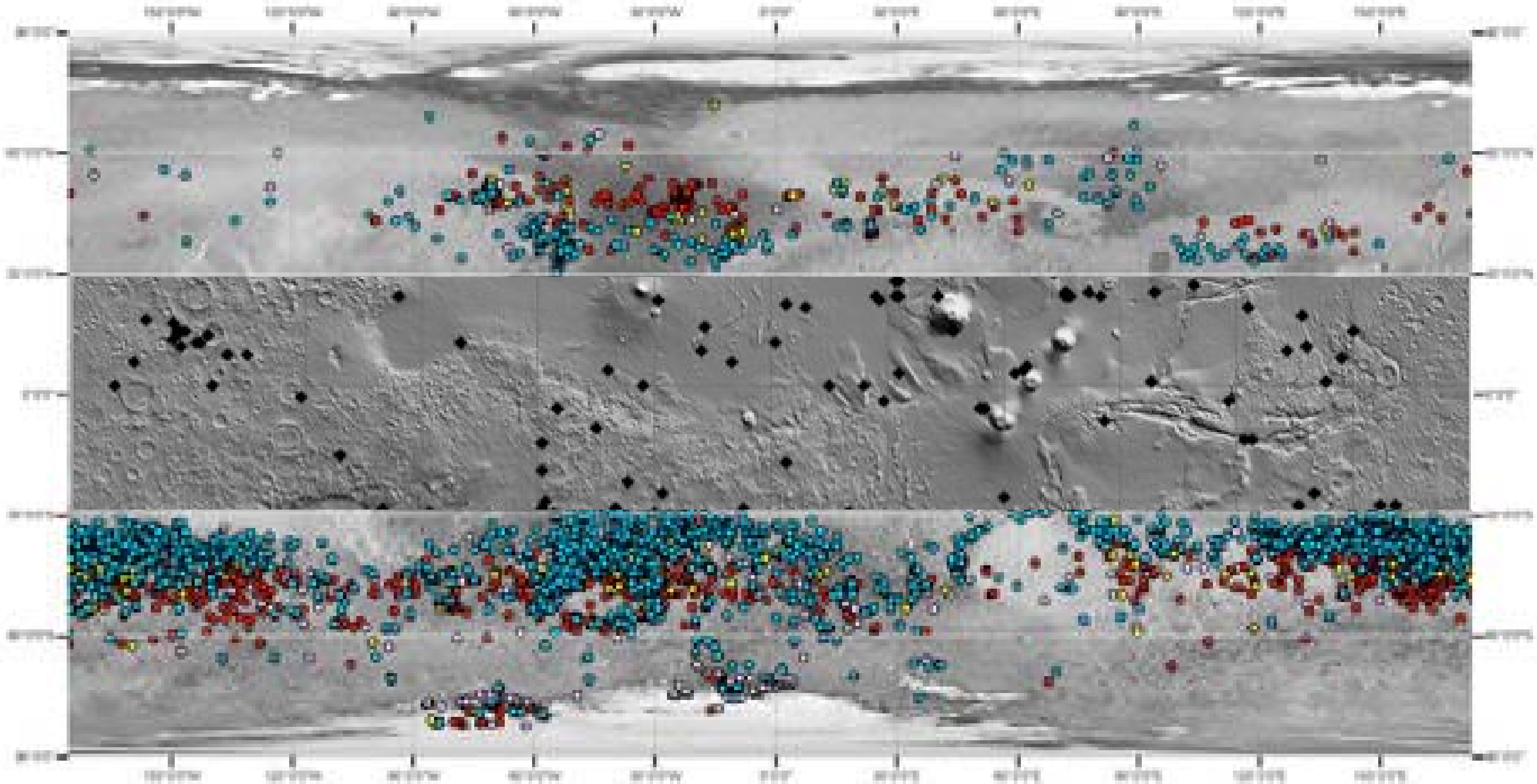
Additional details on RSL in Appendix I

Gullies: Introduction and Taxonomy

The following taxonomy is organized by special regions implications, not by gully morphology.

	Gully Type	Where?	Comment	Proposed SR classification
1	Gullies forming today at CO_2 frost point T	S mid-latitudes (see map on slide 13)	No water involved, or extremely cold brines if they exist.	Not Special
2	Geologically very recent gullies in relatively warm locations spatially associated with ice.	N and S mid latitudes	There is a significant possibility that they formed from past melting of snow/ice during or after high obliquity periods, and since ice still remains, there is potential for reactivation in next 500 years.	Uncertain
3	Geologically very recent gullies NOT spatially associated with ice.	equatorial or mid-latitude equator-facing slopes. Rare near equator except in Valles Marineris	Not known to be active today, except perhaps in Penticton crater (40 S latitude equator-facing slope; season of new bright deposit unknown).	Low probability of being special
4	Small gullies associated with RSL	see map on slide 10	RSL may gradually carve small gullies from water flow.	Uncertain

Global Distribution of Gully Landforms

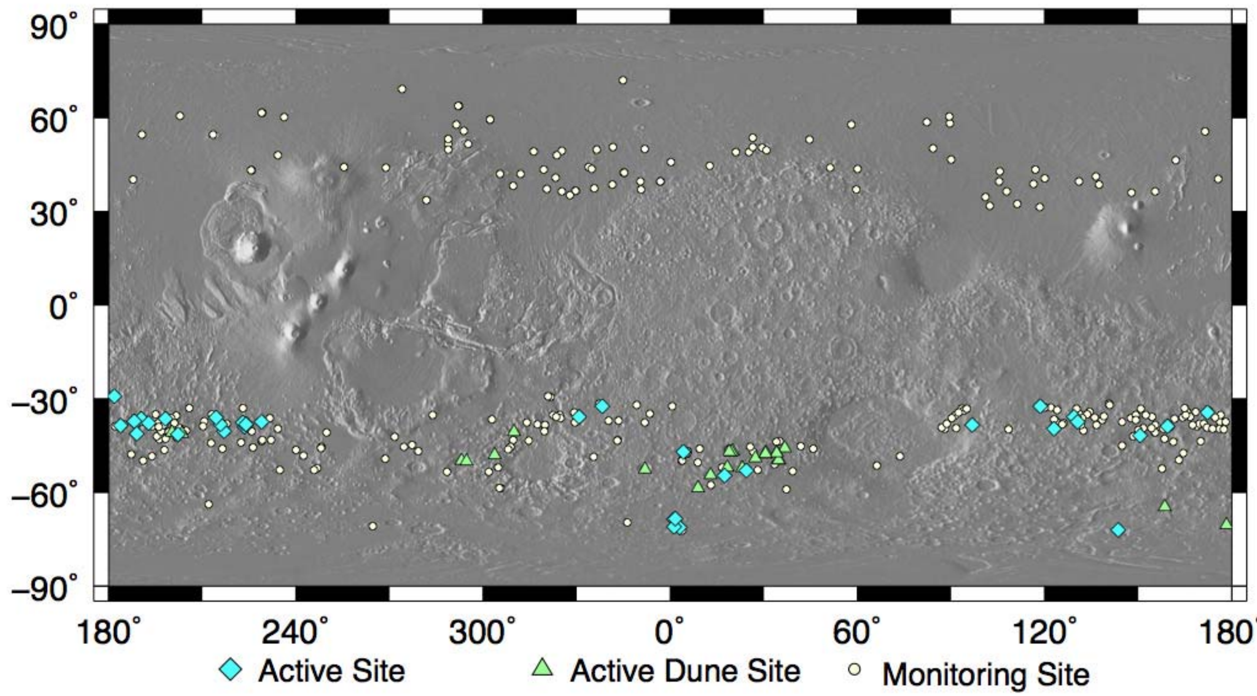


Sources of data:

1. *Colored data points: Harrison et al. (2014). Global distribution of gullied landforms. Colors indicate dominant gully orientation at each landform; blue = pole-facing, yellow = eastwest facing, red = equator-facing, and purple = no preference. Not all these gullies are active. Similar maps have previously been produced by several other authors.*
2. *Black data points: Auld and Dixon (2014). 866 gullies mapped based on images from the first 25,000 orbits of the HiRISE camera using Environment for Visualizing Images (ENVI) 4.4. Mapping criteria did not include age, so these gullies are not necessarily all young, or even episodically active in the modern time.*

Distribution of Gullies Active at the CO_2 Frost Point (Gully Type #1)

- Gullies are actively forming in the current climate, at least in the southern middle latitudes
- They are widespread and occur at all latitudes, but are most abundant in the middle latitudes
- Strong association of known activity with CO_2 frost suggests liquid water does not play a role in mid-latitude gully formation

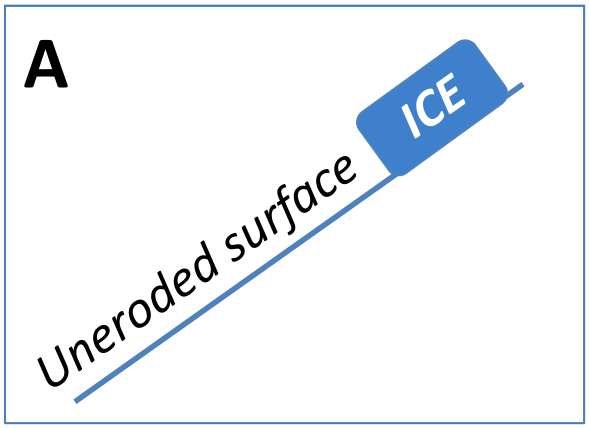


Map of active gullies (excluding small alcove-fan features in N polar sand dunes) vs. monitoring sites. All are located in the S hemisphere where long winters result in thicker seasonal CO_2 deposits.

Finding 2-5: This group of gullies are currently active, but at a temperature far too low to be compatible with liquid water.

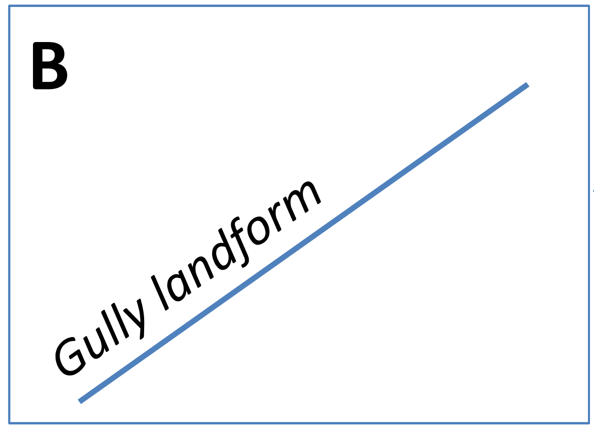
Relationship Between Some Gullies and Ice

PAST CONFIGURATION

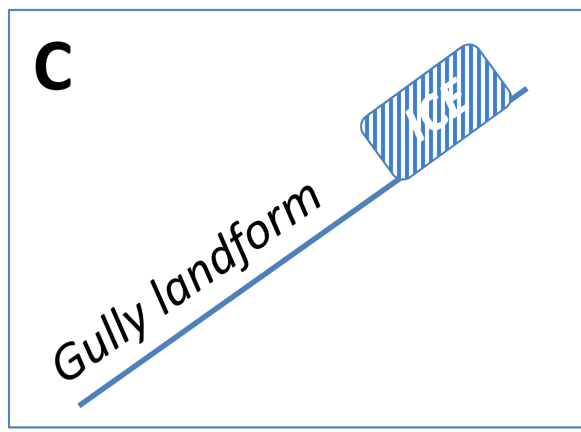


Finding 2-6: Gullies associated with residual ice, if in an appropriate thermal environment, have the potential for liquid water during the next 500 years.

TODAY'S CONFIGURATION



No longer active: Minimal risk of water during next 500 years

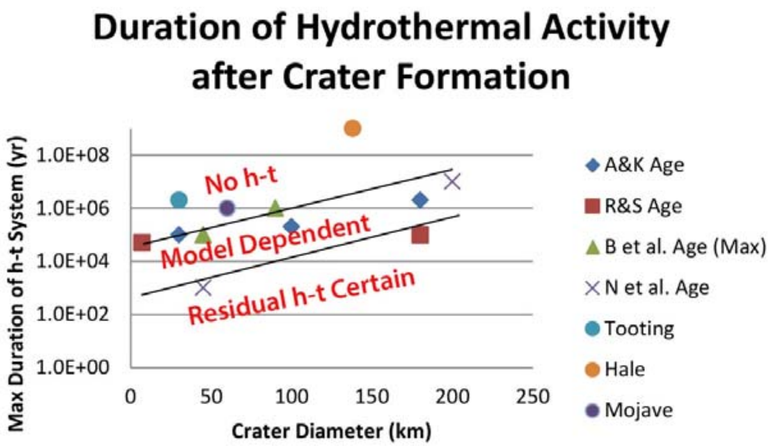


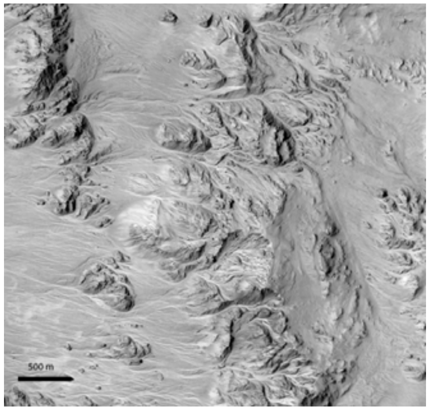
Gullies associated with residual ice have an elevated risk of water during the next 500 years.

The Possibility of Recent Craters that are Still Warm

- Numerical modeling of Martian impact craters suggest that hydrothermal systems could be active on 10^3-10^7 yr time scales, depending on crater size and environment at time of impact. Also, surface discharge can persist for 10^3-10^5 yrs.
- CRISM and OMEGA observations reveal the presence of hydrated silicates in association with Martian impact craters which could have been produced by impact-induced hydrothermal activity.
- We have considered three of the freshest large craters (Tooting, Mojave, and Hale) and find no evidence (either from modeling or observation) that they still retain active hydrothermal systems (plot at right).

Models of the lifetime of hydrothermal systems as a function of crater diameter: A&K = Abramov and Kring, 2005; R&S = Rathburn and Squyres, 2002; B et al. = Barnhart et al., 2010, and N et al. = Newsom et al., 2001. Also shown are three large young craters: Tooting, Mojave, and Hale.





Fans and gullies from water action in 58.5 km diameter Mojave Crater (HiRISE image PSP_001415_1875)

Finding 2-7: Although crater formation ages are highly uncertain, we have not identified any existing craters that have the combination of size and youthfulness necessary for impact-caused hydrothermal activity to persist to the present.

Groundwater

- The MARSIS data set covers about 70% of the martian surface with track spacing less than 30 km. The spatial resolution of MARSIS data is cross track 10-30 km and along-track 5-10 km, depending on the altitude of the spacecraft.
- The SHARAD data set covers < 50% of the surface with a spatial resolution cross track 3-6 km and along track 0.3-1 km.
- Water or brine within a substantial portion of the field of view would present a strong reflection. However, signal attenuation, ground clutter, and spatial resolution limit our ability to detect them.
- There is no evidence for groundwater at a depth shallower than ~200-300 m anywhere on the planet, nor shallower than a depth of 4 km below the polar layered deposits. Below these depths, the data are ambiguous.

Finding 2-8: Within the bounds of several limitations (attenuation, location-specific surface clutter, low spatial resolution, saturated porosity, and surface coverage of the MARSIS and SHARAD radars), groundwater has not been detected anywhere on Mars.

Finding 2-9: We cannot rule out the possibility of near-surface water that may be present at a vertical and/or horizontal scale finer than that detectable by MARSIS and SHARAD.

Thermal Zones on Mars

The THEMIS instrument on Odyssey has investigated the possibility of thermal zones on Mars for >10 years. To date, no local warm zones or hot spots have been identified.

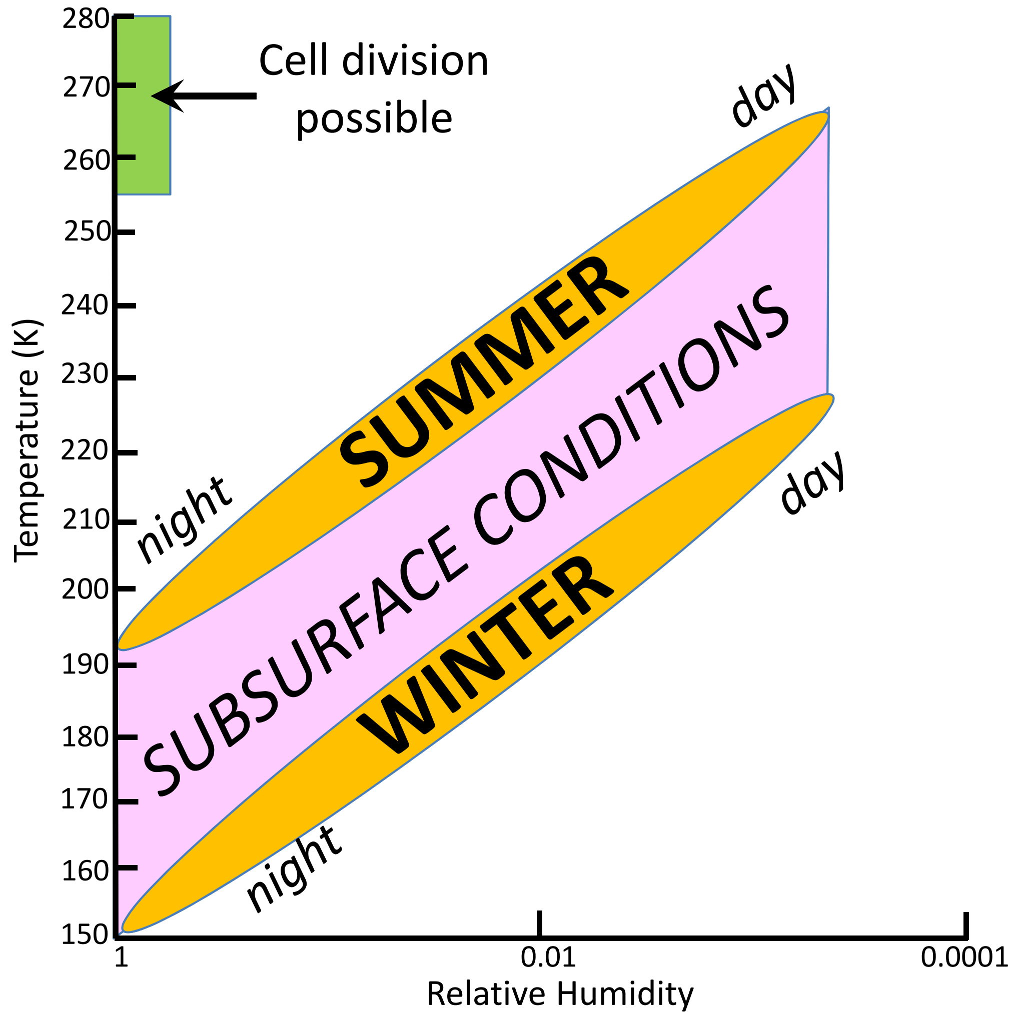
Issues with detection:

- Even substantial sub-surface heat is greatly attenuated at the surface by insulating overburden
- There is significant nighttime thermal variability which makes detecting an anomaly difficult
  - Year-to-year comparisons to attempt to remove these effects and look for long-term internal heat changes have been a challenge because the Odyssey orbit has been changing.
  - Future plans include attempts to correct for local time effects using a more sophisticated thermal model, which has yet to be developed.
- The lack of discovery to date does not eliminate the potential for discovery of near-surface thermal anomalies in the future (Phil Christensen, April, 2014 p. comm).

Finding 2-13: Over a decade of observations by THEMIS have not detected any local hot spots or warm zones, at 100 meter spatial resolution. However, observing conditions have been not been optimal. Future surveys from a modified orbit are being undertaken which should improve the possibility of detecting areas which are anomalously warm. Upon detection of such a zone, independent assessments could then be made to determine whether the zone may also have higher concentrations of water vapor, or other forms of H_2O.

Subsurface Conditions at the PHX Site

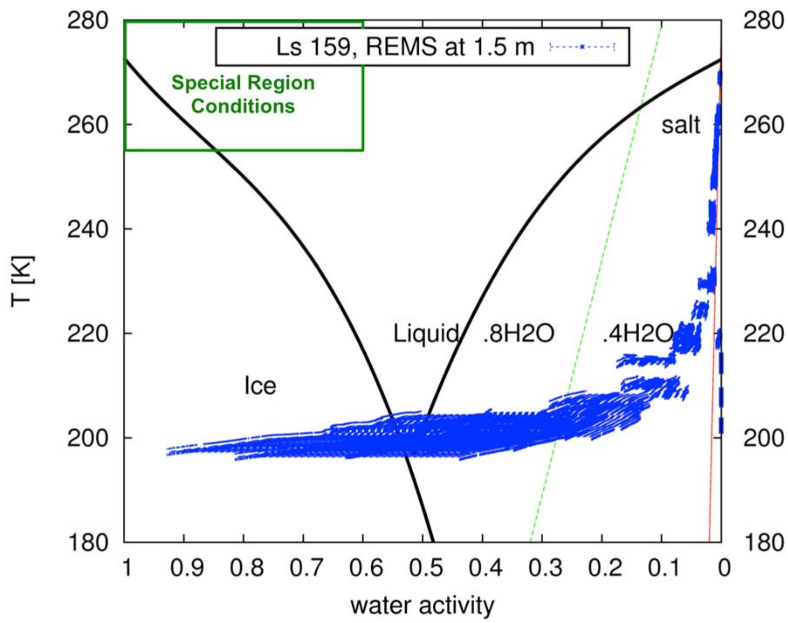
- Phoenix collected data during the summer
- In general, subsurface conditions move towards the average of conditions represented by the diurnal and annual cycles.
- Thin films in the regolith will be at conditions far removed from those needed for cell division.

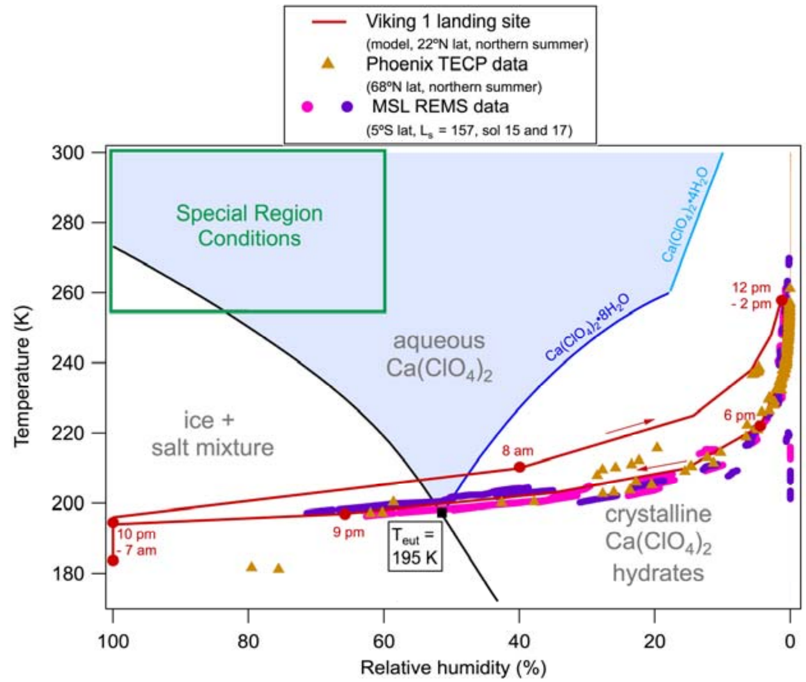


Finding 2-16: Average environmental conditions in the regolith at the PHX site are incompatible with cell division.

Natural Deliquescence on Mars (1 of 2)

Martian environmental conditions plotted on the phase diagram for the calcium perchlorate + water system. For other salts, the aqueous salt (liquid water) field would be shifted to higher T.





<u>Environmental Conditions, MSL site</u>

- Measured by REMS instrument (graphic from Javier Martin-Torres).
- Data for two sols (sols 15-17 after landing). Ls = 159, with ±30% error bars)

<u>Comparison MSL, Viking 1, and PHX</u>

- Note some hysteresis effects associated with warming, cooling during the day.

Natural Deliquescence on Mars (2 of 2)

- The limited results from 2 missions (Phoenix & MSL), as well as conditions modeled at Viking 1, show that the humidity and temperature conditions at all of these locations are, for limited amounts of time, sufficient for the deliquescence of calcium perchlorate (possibly the most deliquescent salt on Mars). Most of the time, however, conditions are too dry or too cold for deliquescence.
- The conditions elsewhere on Mars are not known; however the T and RH data shows only limited variation in the diurnal cycle with latitude or season.
- Metastability (such as supersaturation, supercooling, or metastable deliquescence of lower hydration states) could cause aqueous solutions to exist under a wider range of T/RH conditions and for longer durations than would be predicted by thermodynamics alone.
- If deliquescence does happen at these locations, it does so at a T (<-65°C) far below that needed for cell division (>-18°C).

Finding 2-18: Natural deliquescence of calcium perchlorate, the mineral with the lowest eutectic relevant for Mars, is predicted for limited amounts of time for all three sites.

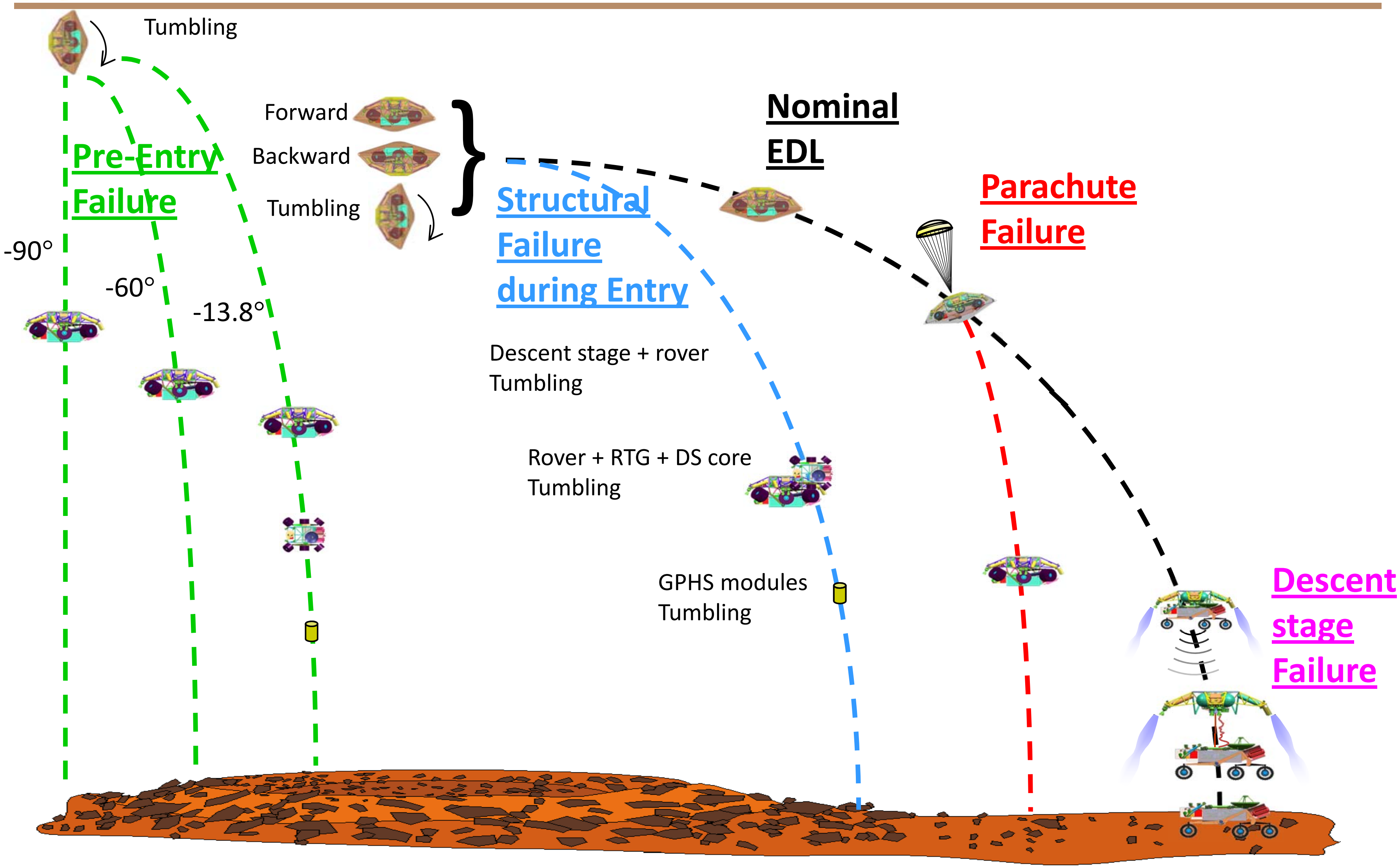
Finding 2-19: The environmental conditions associated with deliquescence at the MSL, PHX, and Viking 1 landing sites are all significantly outside the boundaries of the conditions required for reproduction of terrestrial organisms.

Part 4. Considerations Related to Spacecraft-Induced Special Regions

Topics:

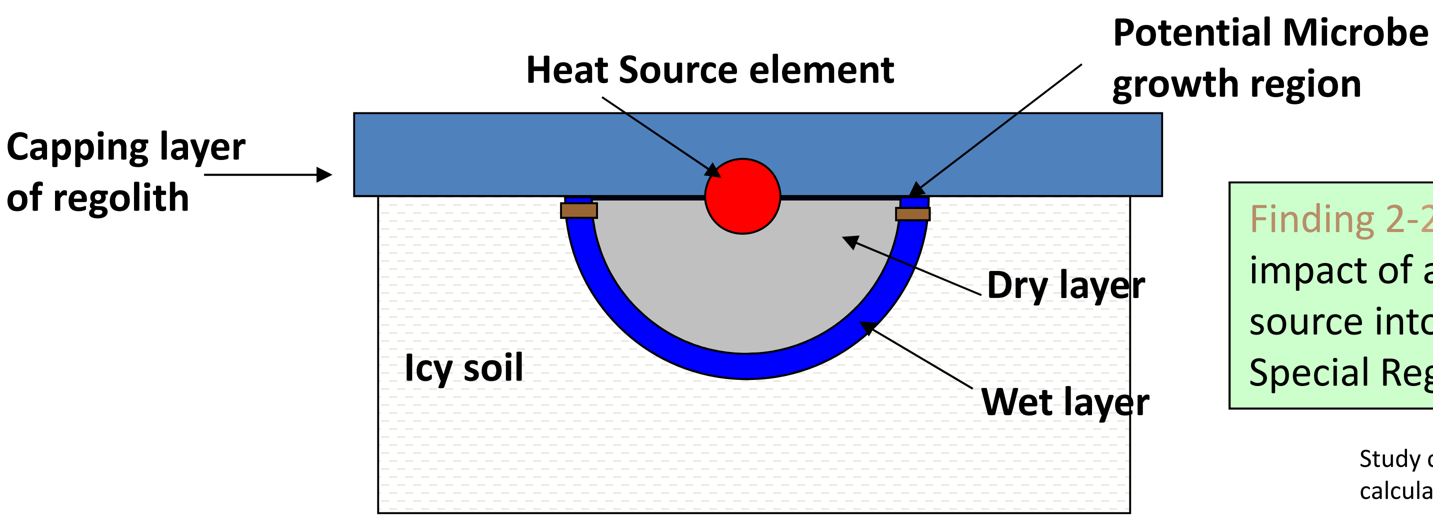
1. Where is there ice within 5m of the surface?
2. Can spacecraft induce deliquescence, and could the results be habitable?

Multiple Failure Scenarios: Breakup During Entry Descent and Landing (EDL)



Example: Thermo-fluid Dynamic Analysis of Buried Heat Source Effects

- General results for analysis
  - The transient thermal wave passes quickly at first then slows down approaching a critical radius beyond which no ice will melt.
  - Moisture content must be above a critical level for reproduction to occur'; that level of moisture is transient and a function of the initial ice content and impermeability of the surrounding regolith
  - Heat source and dried area around heat source become very hot, effectively self-sterilizing
- Net result is that there is a very restricted region near the dry/icy boundary where microbes must be initially located. That region is transient and lasts on the order of 10's of sols, and potentially 100's of sols.



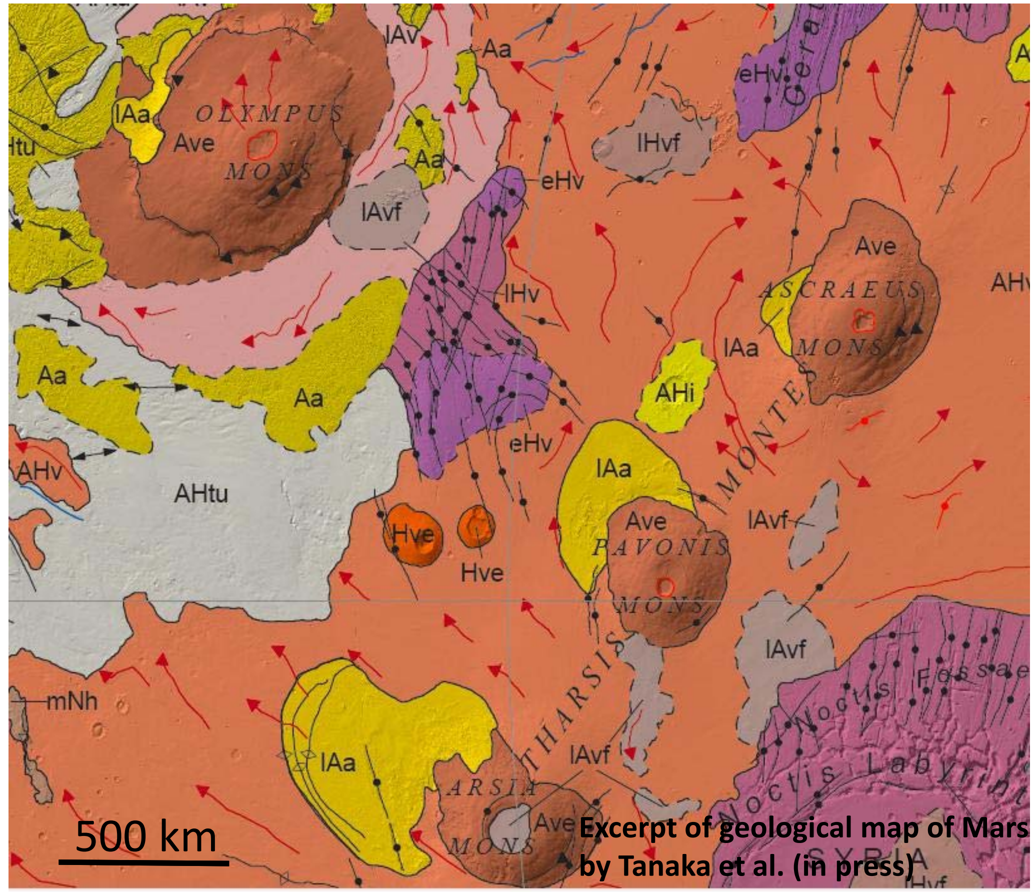
Finding 2-21: A high-speed impact of an isotope heat source into ice could induce a Special Region.

Study conducted at JPL; thermal calculations by Mike Hecht

Tropical Mountain Glaciers

- Map unit lAa of Tanaka et al. (in press) is interpreted to have formed as tropical mountain glaciers.
- There is evidence that there is no residual ice remaining in these deposits within 15 m of the surface.
- It is not known that residual ice exists at any depth within these features (for example it has not been detected by SHARAD), although we cannot prove that it is absent.

240° E

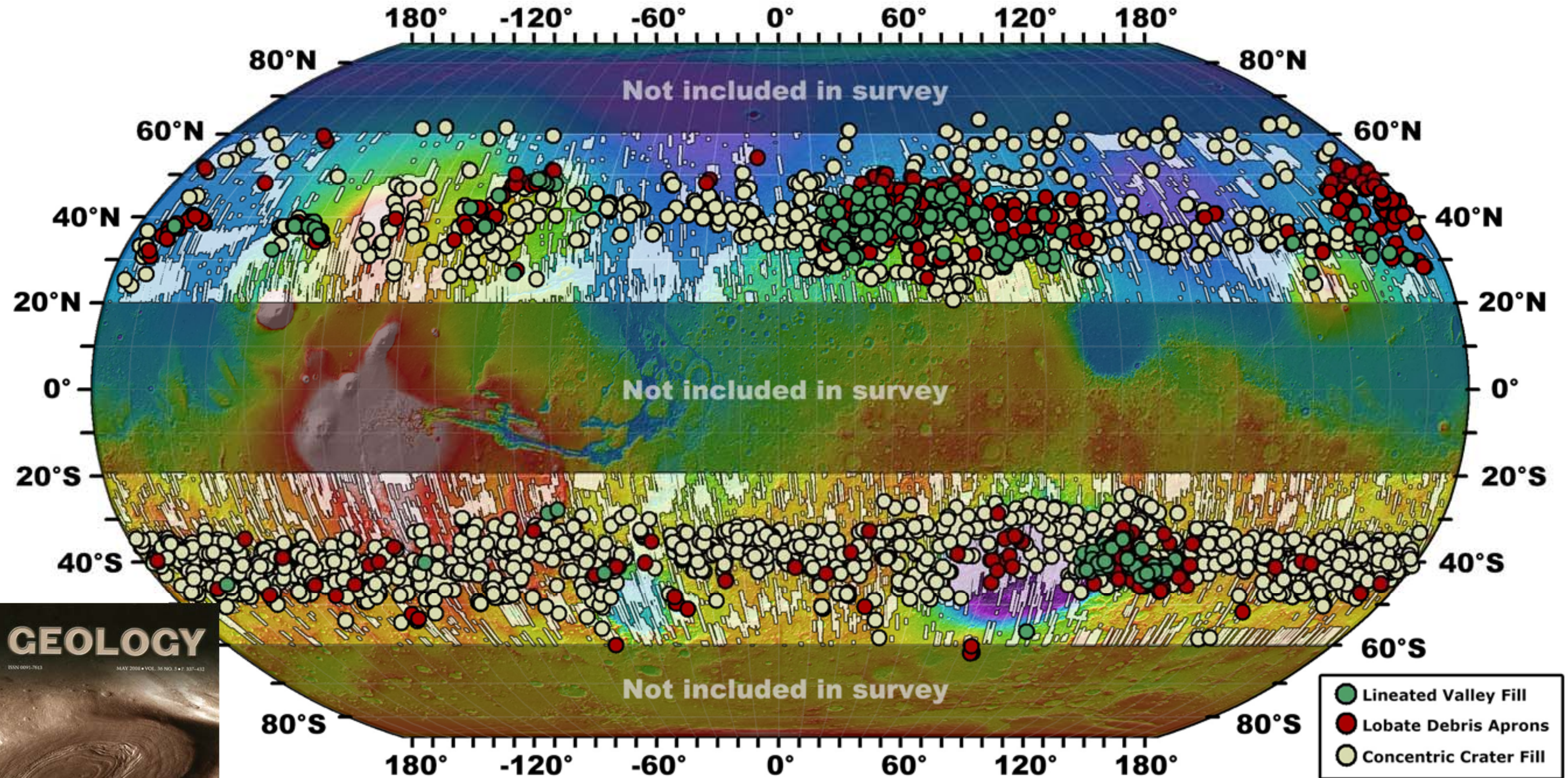


0° N

Excerpt of geological map of Mars by Tanaka et al. (in press)

Finding 2-22: Tropical mountain glacial deposits may contain retain residual ice. However, these deposits are covered with a sublimation lag that is > ~5 m in thickness.

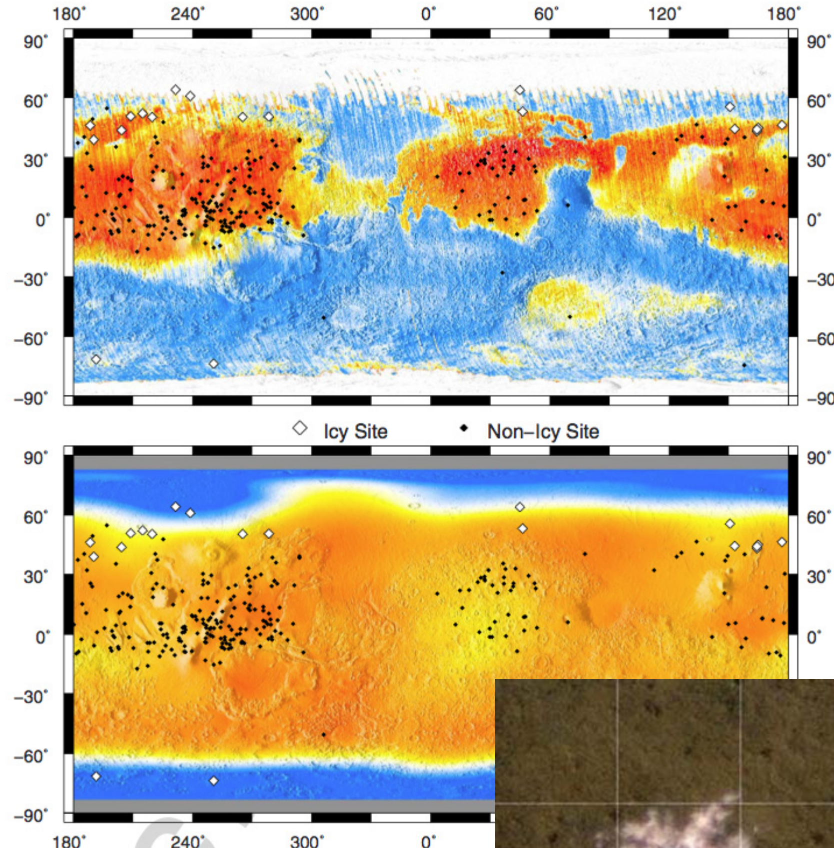
Location of Mid-Latitude Glacial Features

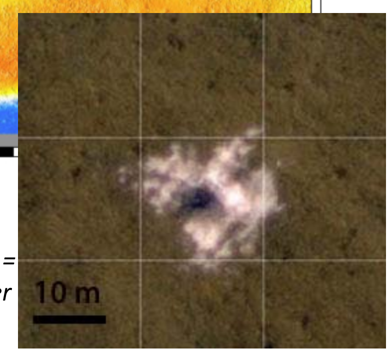


SR – SAG 2

Use of Fresh impacts to Map Ground Ice

- Many new small impact craters in the mid-latitudes expose bright materials in crater interiors and ejecta.
- Bright materials disappear within a few months to years, suggesting it is exposed water ice which sublimates away.
- Suggests relatively pure ice (pore filling ice is not expected to create such albedo contrast).
- Distribution of fresh craters with and without bright materials suggests ice is heterogeneously distributed throughout the mid latitudes. Those without bright ejecta are relatively rare.
- The southernmost extent of the icy impact craters in the northern hemisphere is close to the boundary of expected ground ice, but suggest a long-term average atmospheric water content that is moderately higher (~25 pr. um) than the present value.



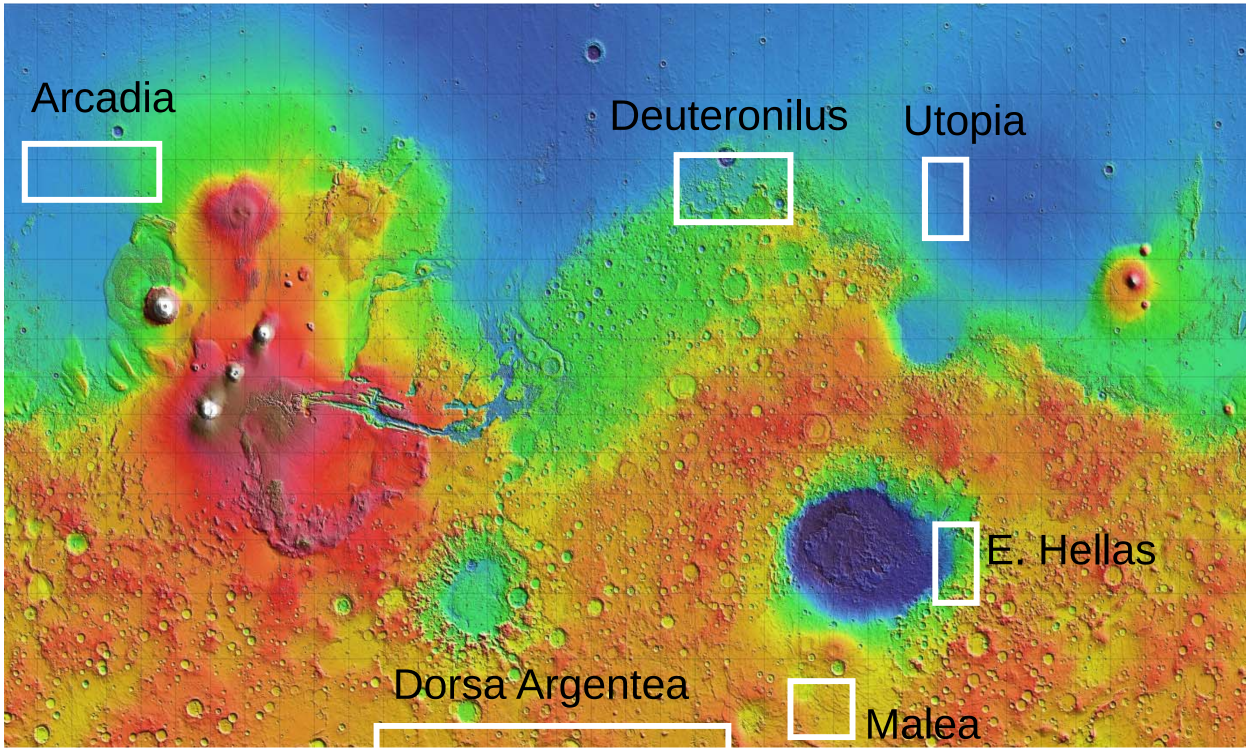


Above: White symbols indicate ice-exposing impacts; black indicates no visible ice. (Dundas et al. 2013). Background of top map is TES dust cover (warmer colors = higher dust content). Background of bottom map is water equivalent hydrogen (warmer colors = lower hydrogen and thus water content). Right: Example crater.

Finding 2-25: Fresh ice exposed by impacts indicates the presence of shallow ground ice at mid and high latitudes, in many cases nearly pure ice, and geographic heterogeneity.

Radar Detection of Non-Polar Ice on Mars

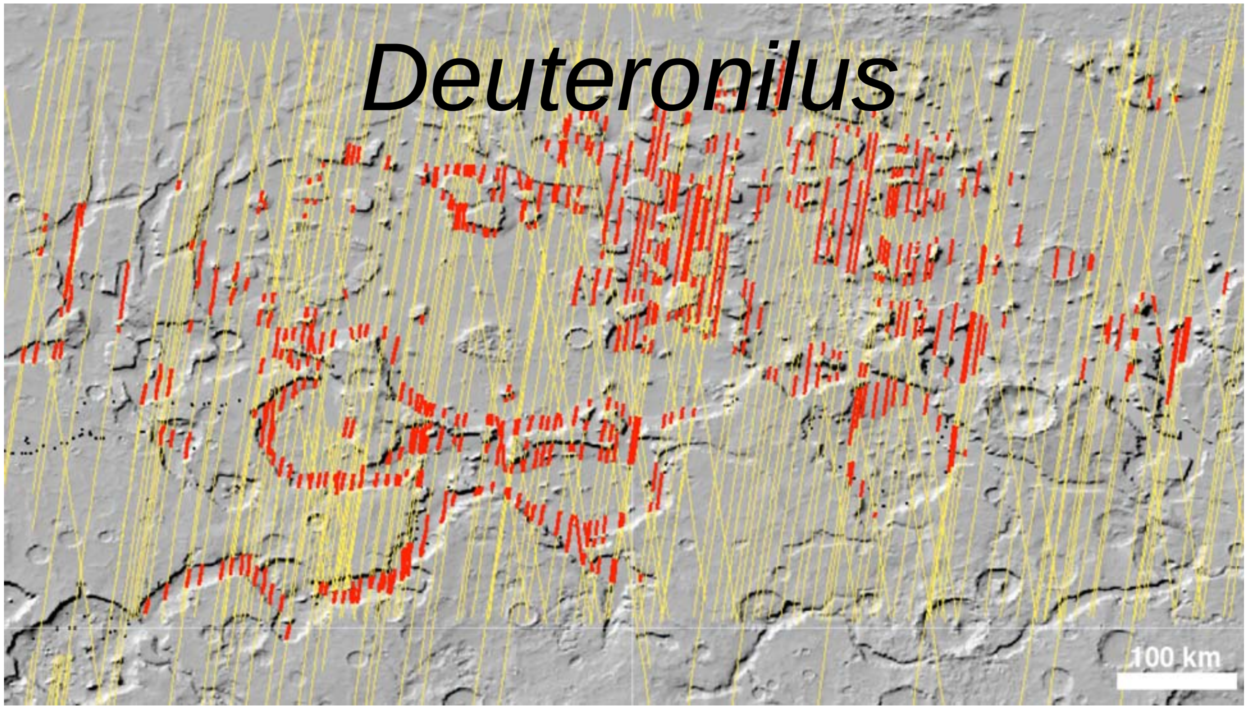
- Ice 100s of meters in thickness has been detected by the SHARAD radar instrument in several regions away from the poles.
- How far below the surface is the ice in these regions? We can only say it's likely to be of the order 10 m.



Summary map outlining areas of subsurface ice detections based on data from the MARSIS and SHARAD instruments. *Source: Jeff Plaut, Roger Phillips, Jack Holt, Than Putzig, and colleagues.*

Radar Detection of Ice

- The vertical resolution of the SHARAD radar allows detection of an ice table if it is deeper than 10 meters and has a sharply defined interface. No such detections have been reported.
- The detections shown here are interpreted to be glacial ice hundreds of meters thick.

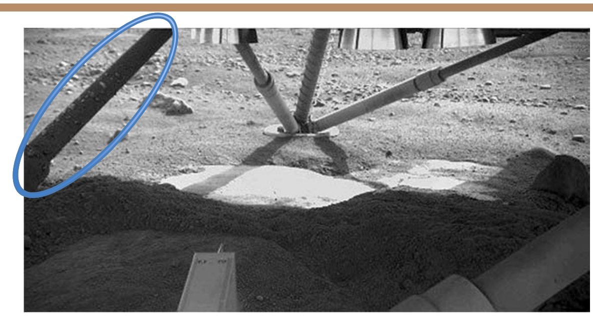


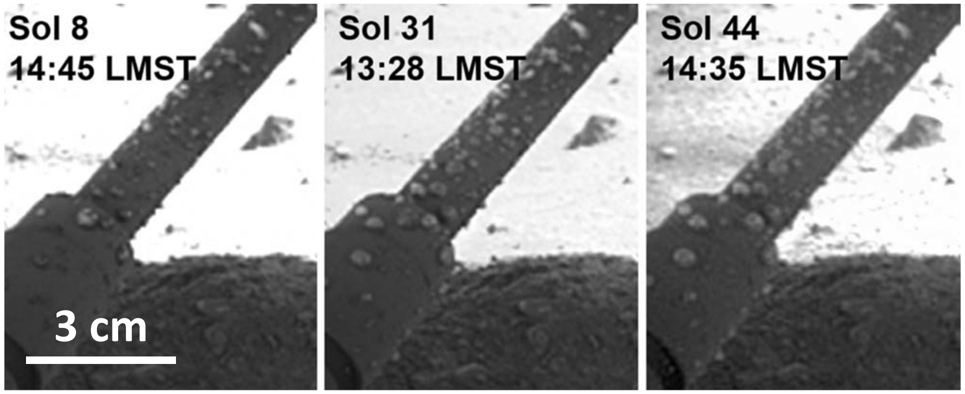
Ice detection by the SHARAD instrument (on the MRO spacecraft), showing the discontinuous nature of thick subsurface ice in the middle latitudes. Source: Jeff Plaut, Roger Phillips, Jack Holt, Than Putzig, and colleagues.

Finding 2-29: In the mid-latitudes, SHARAD has detected subsurface ice at scattered locations.

Spacecraft-Induced Deliquescence: (1) The PHX Strut

- Renno et al, 2009, presented imaging of droplets on a spacecraft strut using the Robot Arm Camera (RAC)
- Propose that splashed soil from thruster interaction with surface on landing adhered to strut
- Propose that drops are oblate spheroids, and grew over the first half of the mission
- Specifically, evidence presented for liquid phase is changing brightness and that one drop apparently merged with another and dropped off
- Atmospheric humidity averages 1.8Pa or <5% RH during day, and ~100% RH at night when cold—no overlap with zone of terrestrial habitability.





The Phoenix lander struts showed spherules that appeared, darkened and disappeared with time.

Finding 2-30: Mineral deliquescence on Mars may be triggered by the presence of a nearby spacecraft, or by the actions of the spacecraft.

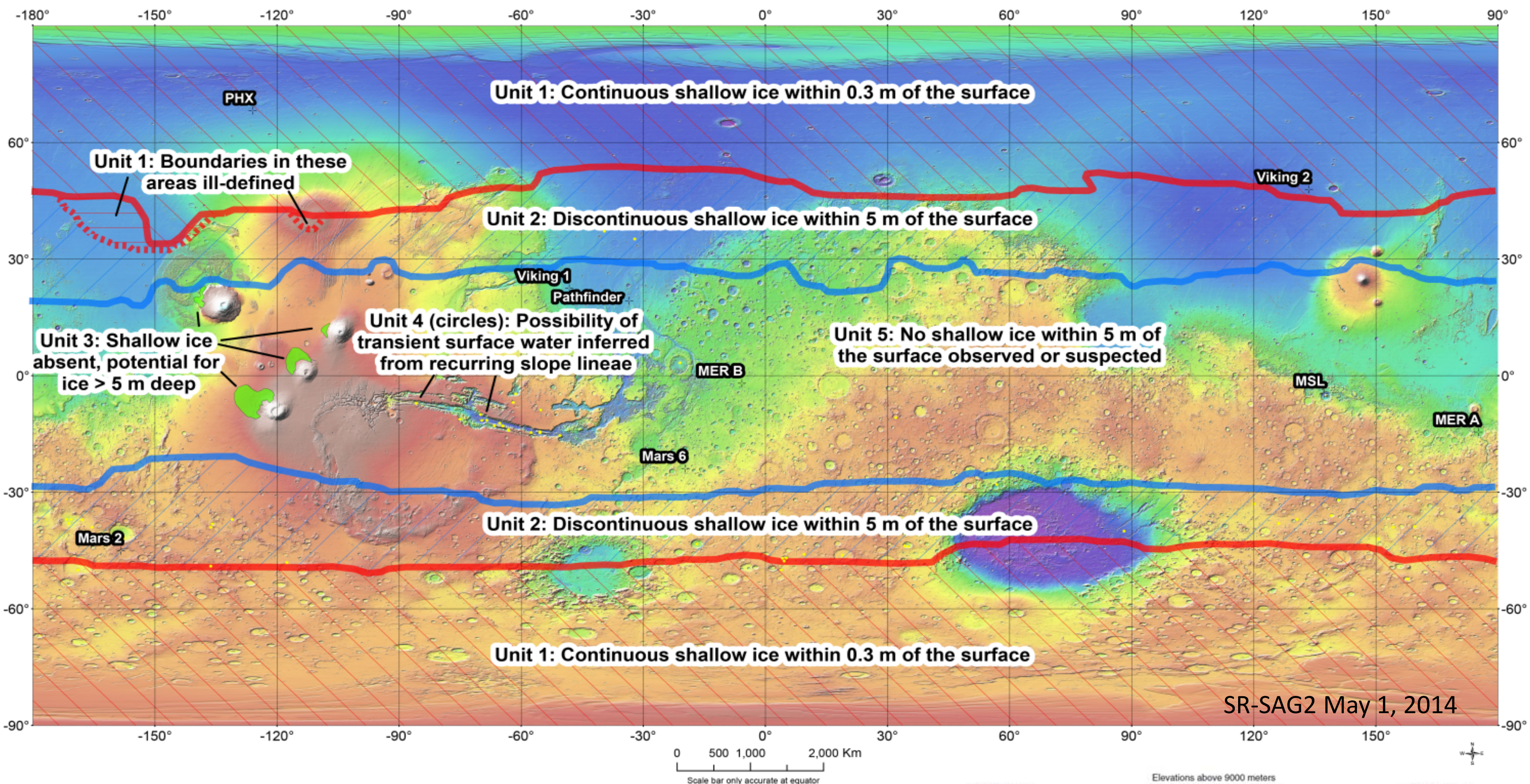
Proposed Classification of Martian Environments

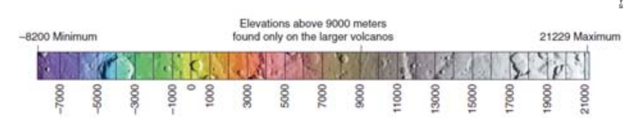
Special	Uncertain But Treated as Special	Non-Special	Would be Special if Found to Exist on Mars
	Caves	Gullies – Taxon 1	Groundwater (at any depth)
	Gullies – Taxon 2	Polar dark dune streaks	Thermal zones
	Gullies – Taxon 3	Slope streaks	Recent craters that are still warm
	Gullies – Taxon 4		
	RSL		

Gullies – Taxa 1: Gullies forming today at CO_2 frost point
Gullies – Taxa 2: Geologically very recent gullies in relatively warm locations spatially associated with ice.
Gullies – Taxa 3: Geologically very recent gullies NOT spatially associated with ice.
Gullies – Taxa 4: Small gullies associated with RSL

Updated from SR-SAG1 (2006) (yellow highlighted cells)

Preliminary Map of Features of Relevance to Interpreting Special Regions on Mars





Background colors represent topography from MOLA.

How to Frame a Recommendation in Light of the Discovery of RSL

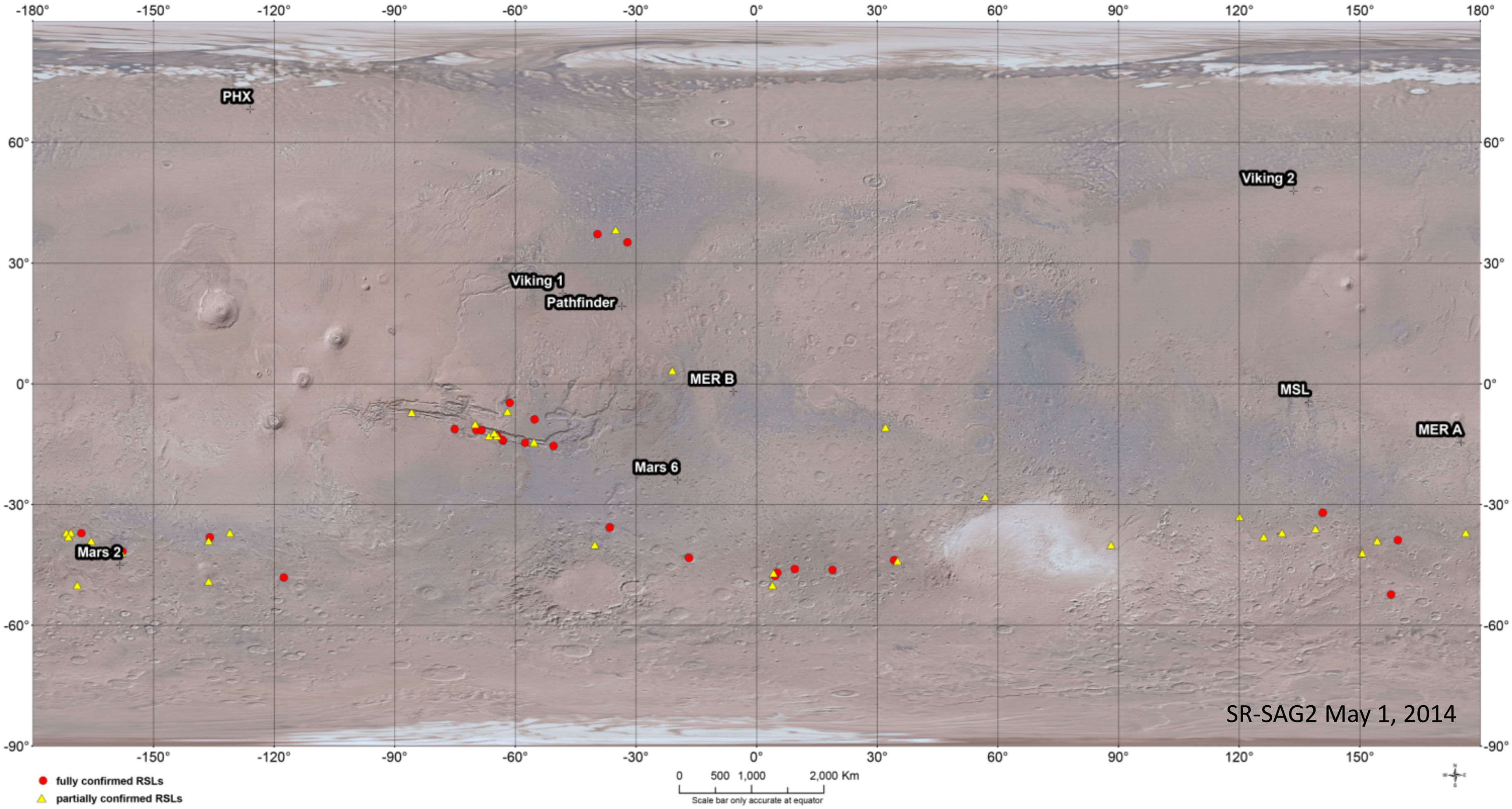
A spectrum of possible RSL-related recommendations

- None, since water isn't proven
  - ✓ Inconsistent with criteria used for other features
- Only confirmed RSL sites
  - ✓ This list is rapidly growing and a moving target
- Confirmed and partially confirmed (partial evidence) sites
  - ✓ Also a moving target
  - ✓ List characteristics
- Add potential candidate sites
  - ✓ Many more sites; includes Gale crater
- All sites with warm temperatures, steep slopes, and low albedo, even where no hint of currently-active RSL (since they may become active in the near future)
  - ✓ much larger list of sites, but cover a very small area of Mars
  - ✓ Problems: how to define limits and how to measure them
- All sites with warm temperatures and low albedo, even if no steep slopes, since the water may be present but just doesn't flow to make detectable RSL.
  - ✓ This one would impact almost all of the 2020 candidate landing sites

SR-SAG2 POSITION → (Confirmed and partially confirmed (partial evidence) sites)

MORE LIBERAL ↕ **MORE CONSERVATIVE**

Map of Confirmed and Partially Confirmed RSL



Proposed Approach Regarding Gullies NOT Spatially Associated with Ice

- Gullies on Mars NOT spatially associated with ice occur in the equatorial belt on warm slopes where CO_2 frost is not likely (Gully Type #3).
- It is considered possible, but extremely unlikely, that one or more of these gullies could be sourced by liquid water from shallow groundwater during the 500-year protection period.

Proposal

- We propose that any mission whose landing ellipse or area of surface operations will include one of these gully features should prepare an analysis of the following:
  - Can a case can be made to constrain the age of activity in the specific gully feature (active, fossil, or unknown)?
  - Are there constraints on whether shallow groundwater is or is not present in the area of the gully?
  - Whether/how the mission is intended to, or might, interact with them.

Proposal on Evaluating Possible Special Regions Induced by Future Missions

- An accurate evaluation of the possibility of Special Regions induced by future spacecraft is highly dependent on the nature of those spacecraft, their heat sources, and their landing locations. Only general guidelines are thus possible at this point
  - However, all surface missions will perturb the local thermal environment to some extent.
- For missions sent to a location underlain by ice, proposers should evaluate the possibility of:
  - melting to form liquid water/brine;
  - the amount of time that liquid might exist;
  - to where it might migrate;
  - what its ranges of water activity and temperature could be.
- For missions sent to a location not underlain by ice, proposers should evaluate the potential presence of highly hydrated salts which, upon heating, could form brine via deliquescence.
  - Evaluate via modeling the environmental conditions of temperature, water activity, and composition of the brine for comparison to the environmental limits for cell division for terrestrial organisms.
  - Evaluate the possibility of brine as a transport mechanism for terrestrial microbes to unknown subsurface environments.

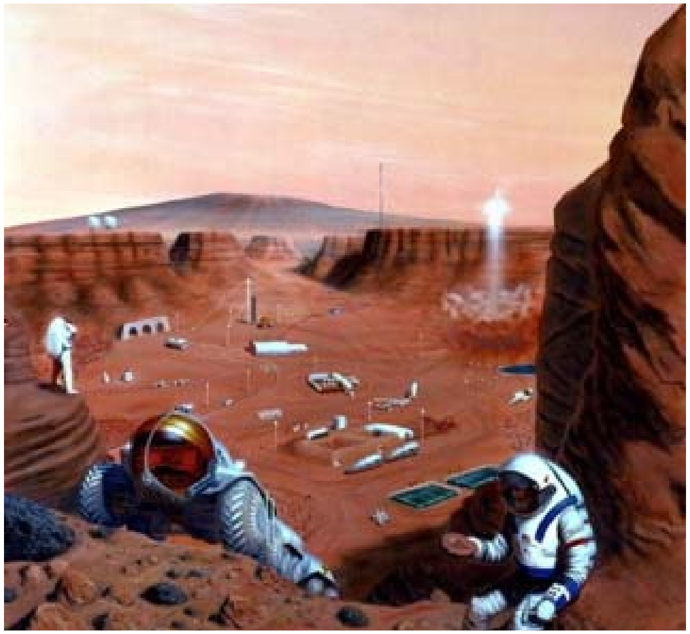
Significant Knowledge Gaps—

If Addressed They Would Help Refine Description of Special Regions

There are major gaps in our understanding of life and Mars that, if filled, would add powerful insights into Mars astrobiology and clarify planetary protection issues.

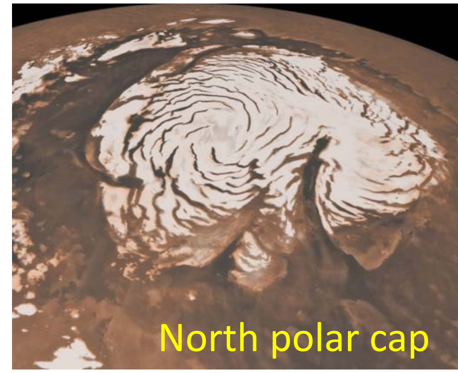
1. The synergy of multiple factors on microbial survival and growth (i.e., storage mechanisms; biofilms and structured microbial communities), and temporal separation in microbial resource use.
2. Studies that consider varying multiple extreme parameters. These should be encouraged, especially those that trade simplicity for the generation of (known) multifaceted extreme conditions.
3. Water activity – additional physiological studies on limits to microbial life.
4. Lower temperature limits for life – additional physiological studies under controlled conditions with a mix of varied parameters across the board.
5. The properties of certain minerals in harsh conditions, such as clays, zeolites and other three-dimensional minerals (for example, sulfides), for the support of microbial life.
6. Understand Phoenix discovery of patches of pure ice that are more concentrated at the site than expected – and the implications of both ice and salt at the Phoenix site.
7. Extend our existing martian datasets in four areas:
    a) Detailed change detection surveys by the HiRISE instrument and follow-ons
    b) Extend the coverage of the radar surveys by MARSIS and SHARAD
    c) Thermal mapping by THEMIS from its new orbit
    d) Continued atmospheric observations from the ground at Gale Crater by REMS

Human Exploration of Mars and Special Regions



- Human exploration of Mars requires access to resources, including
  - Water
  - Oxygen
  - Protection from radiation
  - Fuel for vehicles
- These resources are available on Mars and will require access to surface or near-subsurface materials, some of which may be found in Special Regions
- Special Regions are in part defined on the availability of water, making them a potential source of water and oxygen, in addition to their science value
- Protocols need to be established so that human activities do not inadvertently affect areas designated as Special Regions or cause non-Special Regions to become Special.
  - The spread of terrestrial biological contamination could also impact life support systems, and the availability of Mars resources to human explorers.

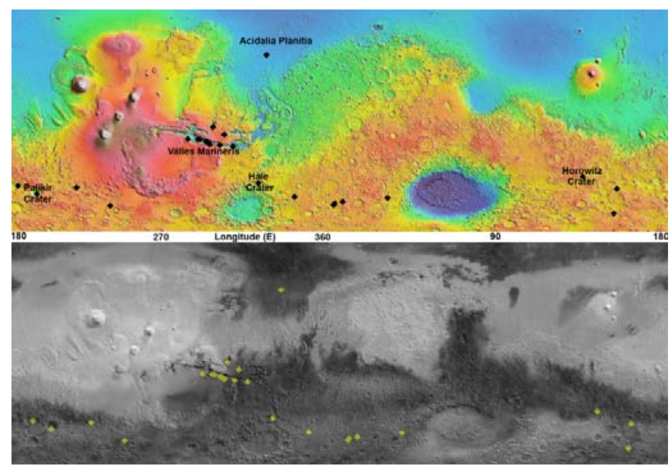
Water Resources



- Polar caps (poleward of ~80° latitude)
  - Seasonal caps are CO_2 ice.
  - Permanent south polar cap is H_2O covered by 3 m thick veneer of CO_2 ice.
  - Permanent north polar cap is H_2O ice
    - ~3 km thick, 1100-km diameter
    - Ice accessible at surface, volume estimated between 1.1 and 2.3 x 10^6 km^3. Freshwater content ~100x the amount in North American Great Lakes.
  - Polar caps are not considered to be Special Regions unless heated to melting
- High Latitudes (60° - 80° latitude)
  - Region largely covered by seasonal caps during winter season
  - As seasonal caps retreat in spring, frost outliers (both CO_2 and H_2O) are left behind
  - Vastitas Borealis Formation, interpreted composed of ice-rich fine-grained (dust) deposits and ice-rich sediments from ancient fluvial activity.
  - New fresh impacts in this region expose ice at depths ranging from 0.3 m to 1.7 m.
  - Not considered to be Special Regions unless heated to melting
  - Accessibility Limitations: Night darkness and cold limit useful season; CO_2 degassing in area may affect safe access by human explorers

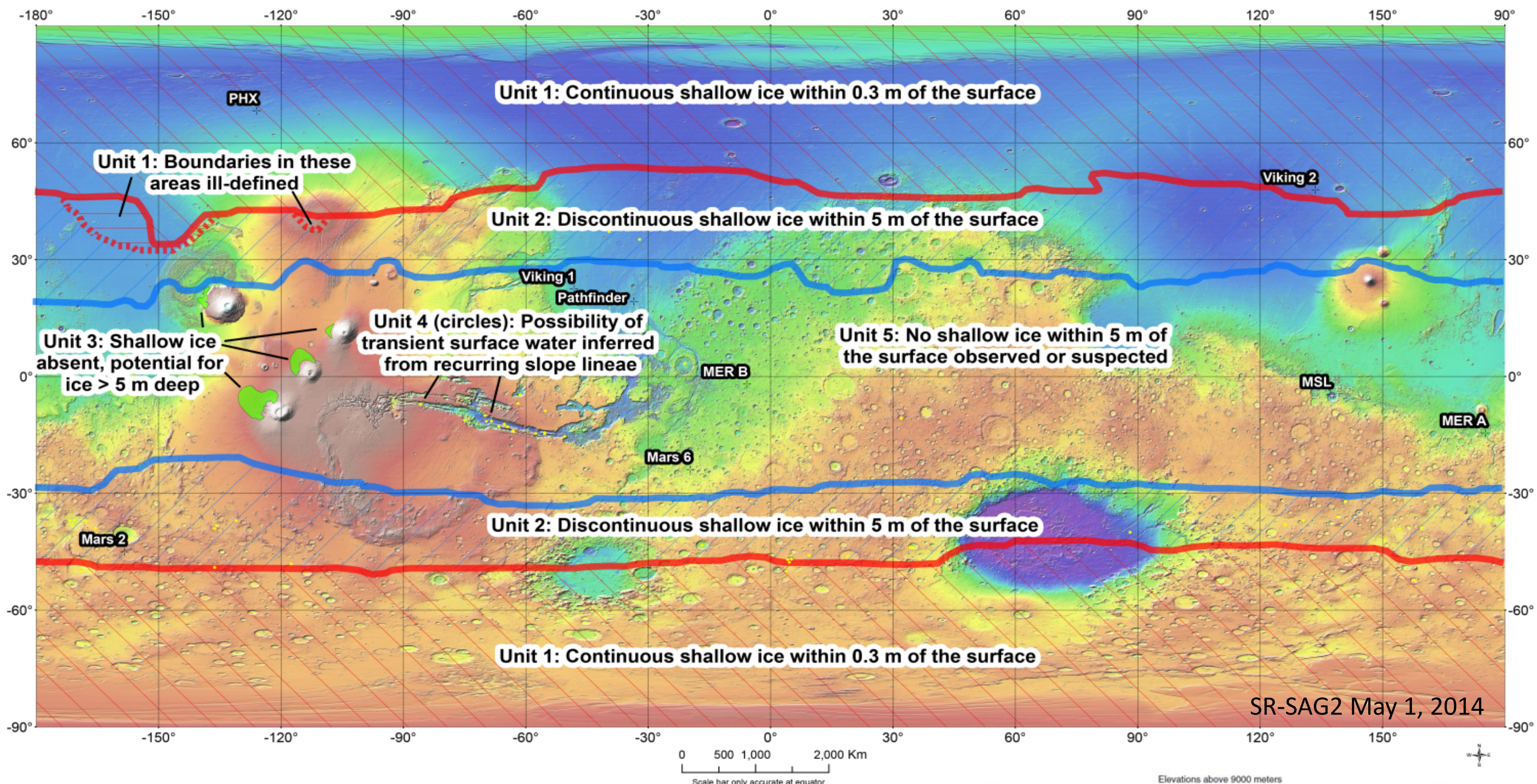
Water Resources

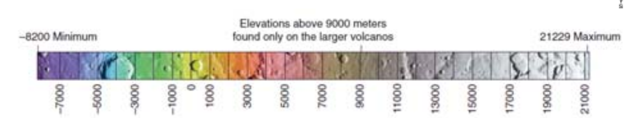
- Mid-Latitudes (30°-60° latitude)
  - Geomorphic evidence of ice-related features emplaced during period of high axial tilt, and evidence of features produced by past possible fluvial activity
  - Recurrent Slope Lineae (RSL) activity concentrated in this zone
  - Fresh impacts expose ice excavated from 0.3-2.0 meters depth
  - RSL sites are treated as Special Regions, and some gullies. Other regions in this zone not considered to be Special unless heated to melting or some future observation points to the natural presence of water
  - Accessibility limitations: Energy produced by solar power limited to summer season
- Equatorial Region (between 30°S and 30°N)
  - RSL sites and potential active gullies suggest presence of near-surface liquid in certain locations
  - Ice deposits from past periods of high axial tilt remain at depth (>15 m) in localized regions
  - Subsurface ice is generally located at depths >5 m in this region and often >50 m depth.
  - Accessibility limitations: High levels of solar energy and warmest temperatures on the planet, but limited accessibility to H_2O.



Distribution of confirmed RSLs.

Preliminary Map of Features of Relevance to Interpreting Special Regions on Mars





Background colors represent topography from MOLA.

Water/Oxygen ISRU

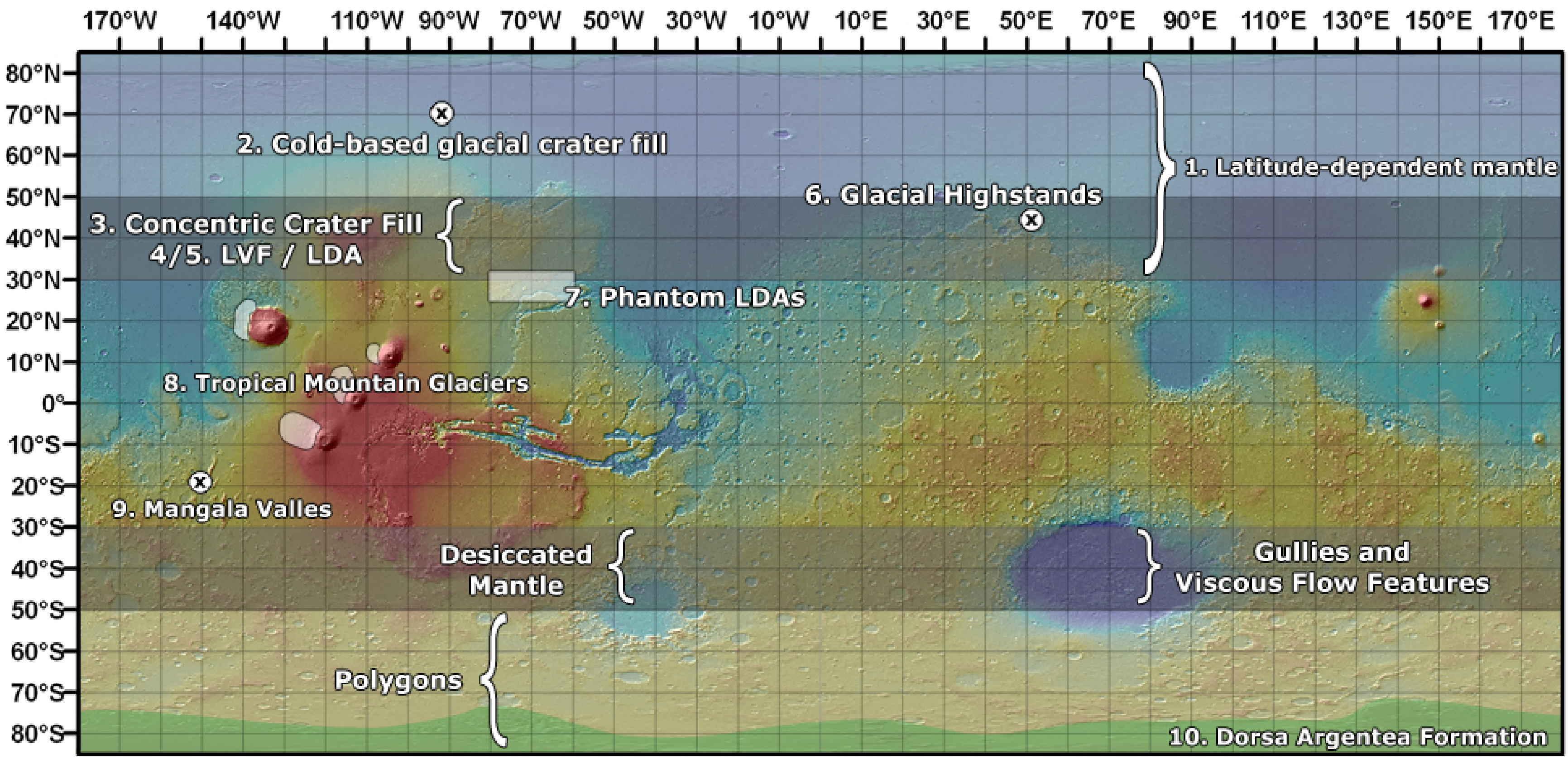
- Atmosphere
  - Water vapor varies seasonally but overall is small amount compared to surface resources. Condensation of all H_2O vapor in atmosphere would produce ~1 km^3 of liquid.
  - Martian atmosphere consists of mostly CO_2, which can be utilized to produce oxygen; water is found in Martian regolith materials.
  - Limitations: Energy to run CO_2 electrolysis systems, regolith baking ovens and water vapor condensers; Dust in Martian atmosphere, particularly during dust storm periods, could clog atmospheric ISRU.

H_2O clouds in pre-dawn sky from Mars Pathfinder

Martian dust devil seen from orbit

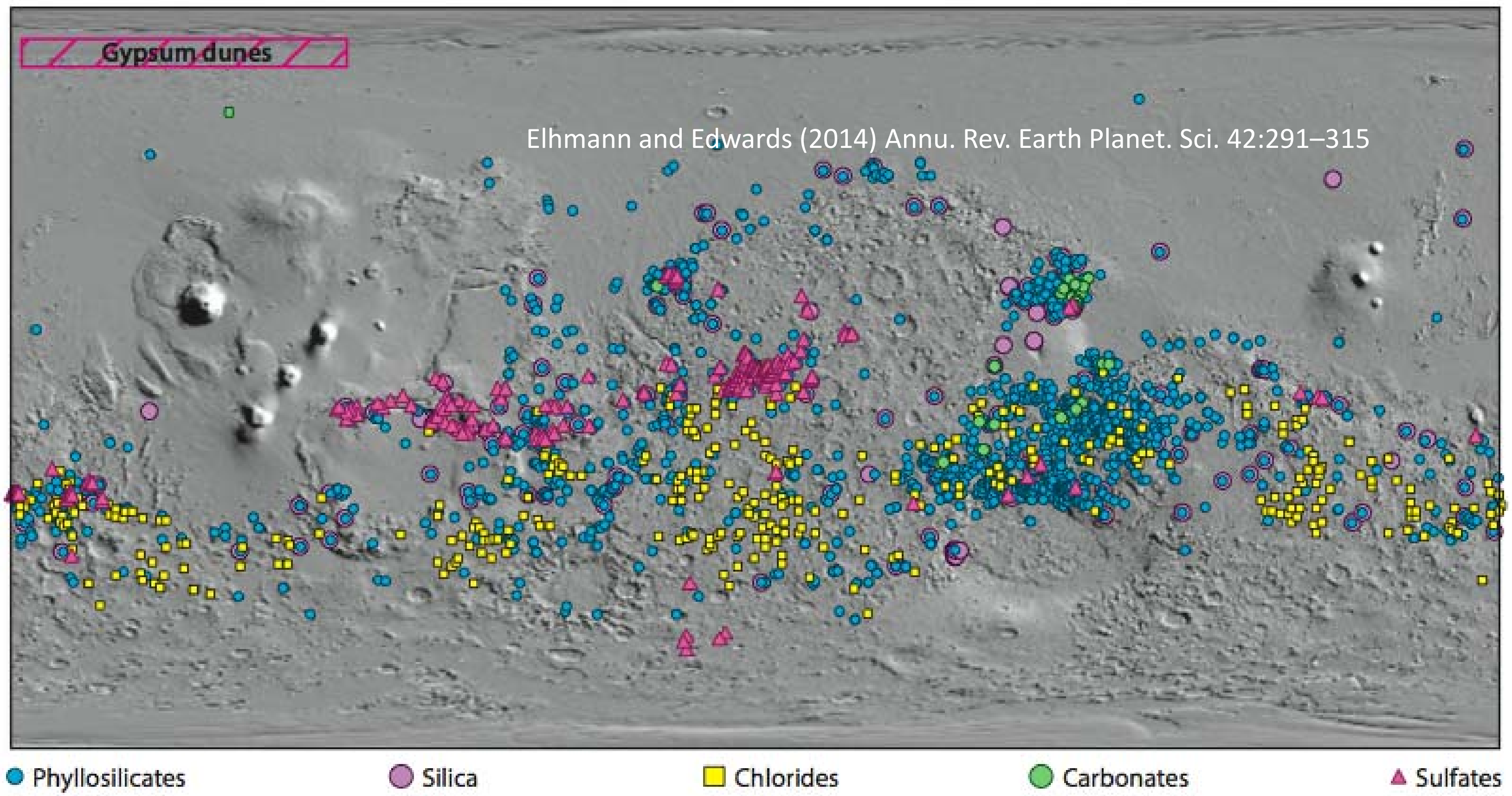
Water/Oxygen ISRU

- Surface resources
  - Surface and near-surface (<3 m depth) ice deposits could provide H_2O and O_2



Water/Oxygen ISRU

- Surface resources
  - Hydrated minerals (phyllosilicates, sulfates, and carbonates) in localized regions could be used to extract H_2O and O_2. Chlorides are largely anhydrous.



Water/Oxygen ISRU

- Perchlorate
  - Perchlorate (ClO_4^-) has been detected at Phoenix and MSL landing sites *(Hecht et al., 2009; Glavin et al., 2013)* and in one martian meteorite *(Kounaves et al., 2014).* Expected to be common in Martian regolith across planet.
  - Perchlorate and chlorides could be a source of ISRU-derived O_2 or propellants *(Davila et al., 2013).*
  - However, perchlorate is toxic to humans. Presence in dust, groundwater, and in crops grown in Martian soil needs to be reduced for human activities to be successfully conducted on Mars *(Davila et al., 2013).*

Radiation Environment

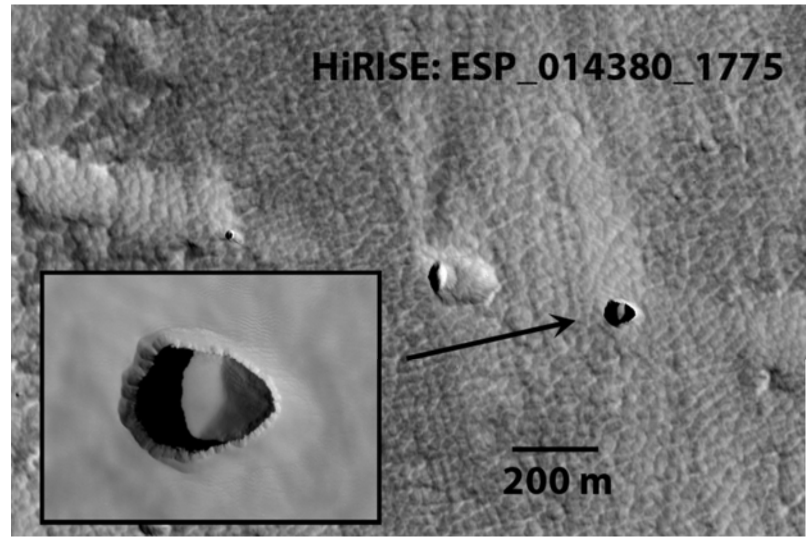
- The thin atmosphere, small concentrations of atmospheric ozone, and lack of a present-day active magnetic field result in radiation reaching the martian surface from space.

- The Radiation Assessment Detector (RAD) on the Mars Science Laboratory's Curiosity rover has measured galactic cosmic ray (GCR) and solar energetic particle (SEP) doses at the surface *(Hassler et al., 2014)*.

Depth (m)	GCR Equivalents (mSv/yr)	GCR Dose Rate (mGy / yr)
0	232	76
0.1	295	96
1	81	36.4
2	15	8.7
3	3	1.8

Radiation Shielding

- A round trip Mars surface mission of 360-day round-trip (180 day each way) cruise and 500 days on the surface is estimated to result in a total mission dose equivalent of ~1.01 Sv, based on MSL cruise and surface radiation measurements *(Hassler et al., 2014).* Doses could be higher if operations occur during periods of higher solar activity.
- Current federal occupational limit of radiation exposure per year for an adult is below ~0.05 Sv. Thus shielding is required for long-term surface operations.

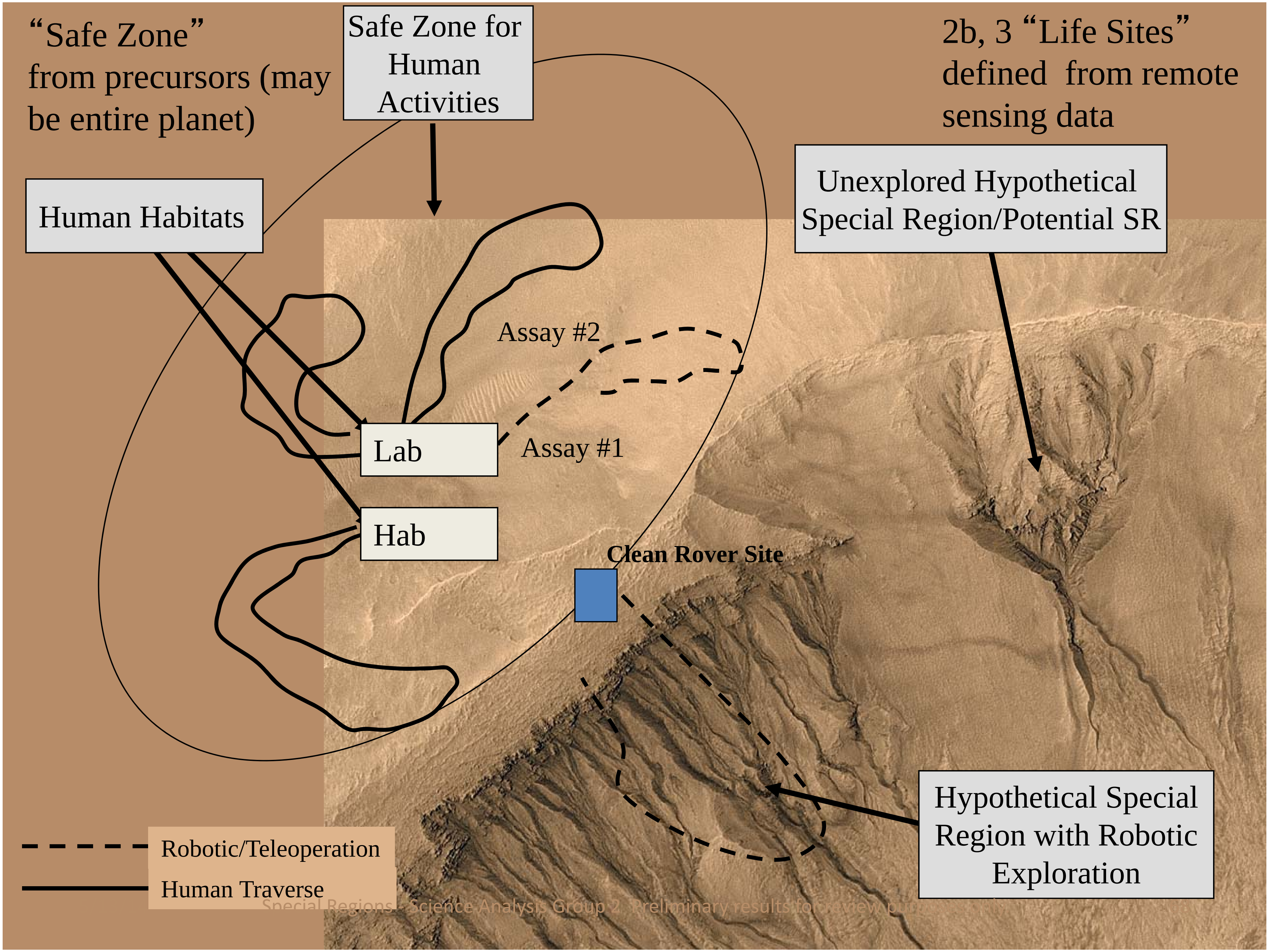


Collapsed pits associated with extensional tectonics, northeast of Arsia Mons. Images: NASA/JPL/University of Arizona. Composited by G. Cushing.

- Deposition of regolith over surface habitats, water storage both in tanks and as ice around habitats, or erection of habitats underground (perhaps in lava tubes/caves) would provide the necessary shielding from radiation.
- Remnant crustal magnetism in a few locations in the highlands may provide some partial shielding from cosmic radiation.

Limiting Contamination of Special Regions by Human Activities

- It will be not be possible for all human-associated processes and mission operations to be conducted within entirely closed systems.
- Human missions to Mars shall not affect or otherwise contaminate Special Regions of Mars, nor be contaminated by materials from them.
- Human activities on the surface of Mars shall avoid converting areas into Special Regions, such as through the melting of surface/near-surface ice by waste heat.
- One scenario: establish “safe zone” for human activities near Special Regions, but allow controlled robotic access to the Special Region locations, themselves, as depicted on the next slide, which implies:
  - Ability to land a “clean” robotic rover in the same area as the human landing site
  - System capability to aseptically interact with rover and receive contained, rover-collected samples.


"Safe Zone" from precursors (may be entire planet)
Safe Zone for Human Activities
2b, 3 "Life Sites" defined from remote sensing data
Human Habitats
Unexplored Hypothetical Special Region/Potential SR
Assay #2
Assay #1
Lab
Hab
Clean Rover Site
Hypothetical Special Region with Robotic Exploration
Robotic/Teleoperation
Human Traverse

Summary of Resources and Relationship to Special Regions

Resource/Activity	Sources	Special Region Concerns
H_2O Resources	Surface and near-surface	RSL sites and possibly active equatorial gullies are treated as Special Regions. Other regions may become special if ice is heated to melting.
ISRU	Atmosphere, H_2O deposits, hydrated minerals, perchlorate	Same as for H_2O Resources.
Radiation Shielding	Regolith and/or water over habitat; underground (caves/lava tubes).	Natural caves/lava tubes may be Special Regions.
Other Fuel and Power (not shown)	Atmosphere, surface materials, perchlorates, solar energy, nuclear power	May become Special if surface/subsurface ice is heated to melting.

Backups

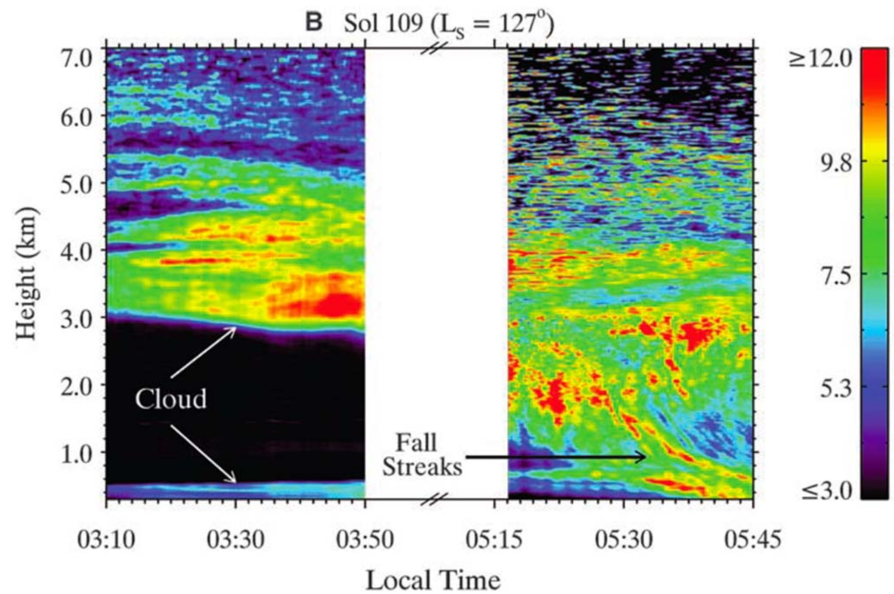
Gullies: Summary Interpretations

The SR2-SAG committee is in agreement with the following conclusions:

- Most of the current gully activity on Mars for which seasonal constraints are available (by means of careful change detection surveys by the HiRISE instrument on MRO) occurs at the CO_2 frost point, and is thermally incompatible with the presence of liquid water. Rare activity seen at warmer temperatures is consistent with dry mass wasting on steep slopes.
- However, some of the erosion in these gullies may have been accomplished by liquid water, most likely in a prior (warmer) climatic environment. Such liquid could have originated through the melting of surficial ice deposits that had been laid down in the last glacial period, which culminated a few hundred thousand years ago.
- There is nothing in either the MARSIS or SHARAD data sets that is suggestive of shallow groundwater origin for the gullies (and such features would be at sufficiently shallow depth on crater walls and scarps that any associated reservoir of subsurface liquid water should be clearly visible in the orbital radar data).
- The potential for a gully to have liquid water during the next 500 years is primarily dependent on a) its association with residual ice that has not yet melted, or b) its association with RSL, for which a water-related genesis is possible but not proven.

Impact of Potential Snow Deposits on Deliquescence

- Snowfall that reached the ground was observed by PHX on sol 109 between 5 and 6am. Snow deposits could not be distinguished from frost. (Whiteway et al, Science, 2009).
  - Ice Water Content of cloud column estimated to be very low at 1.9 pr μm
- Snow is not included in current models of the Mars hydrological cycle. There is a potential for a snow crystal out of equilibrium with the surface environment to come in direct contact with a salt crystal (Stoker et al, JGR-E, 2010)
  - Snow may occur in equatorial regions (30N to 10S) associated with the Aphelion Cloud Belt



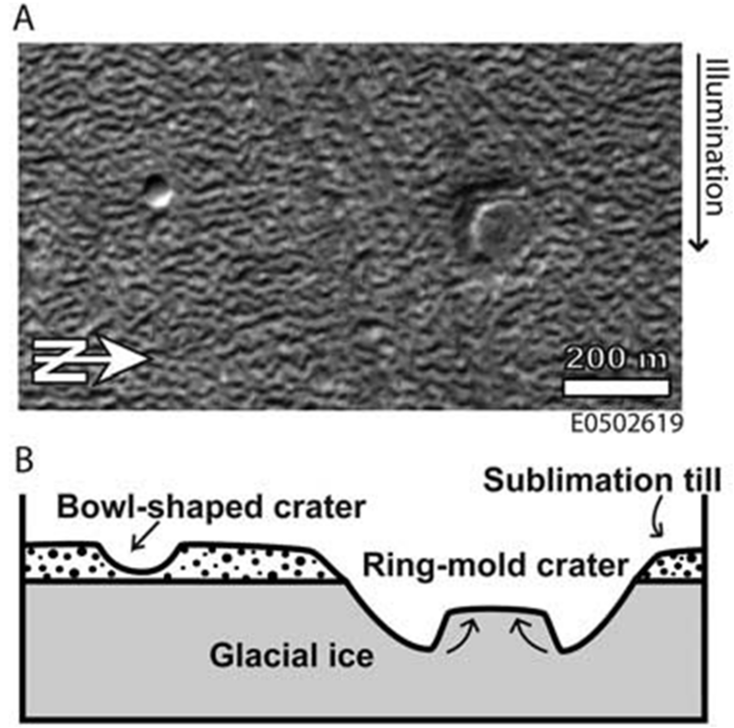
Cloud and snowfall observed by PHX LIDAR on Sol 109.

Snow deposits could generate localized accumulations through drift

Finding 2-20: While snow may be deposited in Equatorial regions and elsewhere, its volume is thought to be negligible, and expected during the coldest part of the night.

Depth to Tropical and Mid-Latitude Ice Deposits

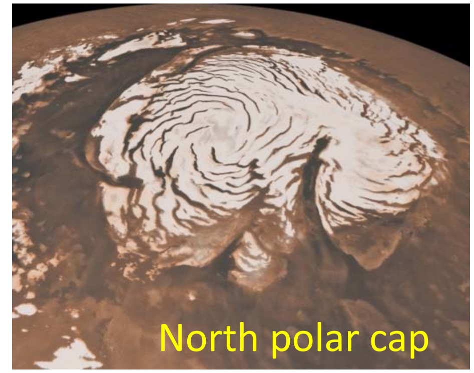
- Two major methods exist for determining the thickness of the sublimation lag overlying the deposits:
  - SHARAD radar measurements (Holt et al., 2008; Plaut et al., 2009),
  - morphology of distinctive superposed crater, known as Ring-Mold Craters (Kress and Head, 2008).
- RMCs are interpreted to owe their distinctive morphology to excavation through the sublimation lag into buried ice; small bowl-shaped craters (BSC) penetrate only into the sublimation lag. Crater diameter frequency distribution reveals the thickness of the lag.
- For mid-latitude CCF, LDA and LDF, analysis of populations of BSC/RMC indicate that the typical thickness of the sublimation lag is at least 15 meters.
- For SHARAD data, where subsurface ice is detected in RMC areas, the overlying sublimation lag is not detected by SHARAD so must be less than the "detection thickness" of about 15 m.
- The Latitude-Dependent Mantle (LDM) (Head et al., 2003), apparently discontinuous between 30^{o}-50^{o} N and S latitude, and continuous from 50^{o} N and S latitude to the poles, is very young and the sublimation lag is generally significantly less than 5 meters as indicated by fresh superposed craters, gamma-ray spectrometer data, and Phoenix observations.



Detecting Buried Ice: Bowl-Shaped Craters (BSC) and Ring-Mold Craters (RMC) on Lineated Valley Fill (LVF) (A); (B) Cross-section showing interpreted relations to buried ice (Kress and Head, 2008)

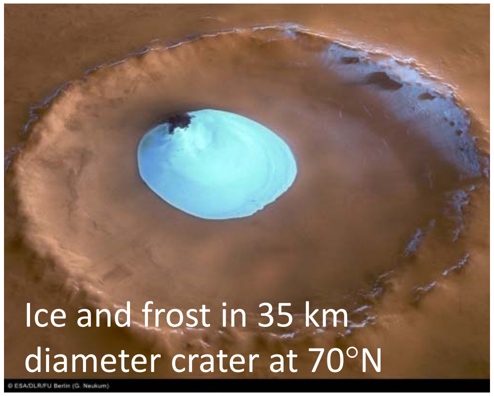
Finding 2-23: Depth to buried ice deposits in the tropics and mid-latitudes is >5m, except Latitude-Dependent Mantle.

Water Resources



- Polar caps (poleward of ~80° latitude)
  - Seasonal caps are CO_2 ice.
  - Permanent south polar cap is H_2O covered by ~8 m thick veneer of CO_2 ice.
  - Permanent north polar cap is H_2O ice
    - ~3 km thick, 1100-km diameter
    - Volume estimated between 1.1 and 2.3 x 10^6 km^3. Freshwater content estimated to be ~100x the amount in North American Great Lakes.
    - Ice accessible at surface
    - Estimated to be 90-100 wt% H_2O, mixed with dust from global dust storms
  - Polar caps are not considered to be Special Regions unless heated to melting
  - Accessibility Limitations: Polar night darkness and cold limit useful season; CO_2 degassing in area may affect safe access by human explorers

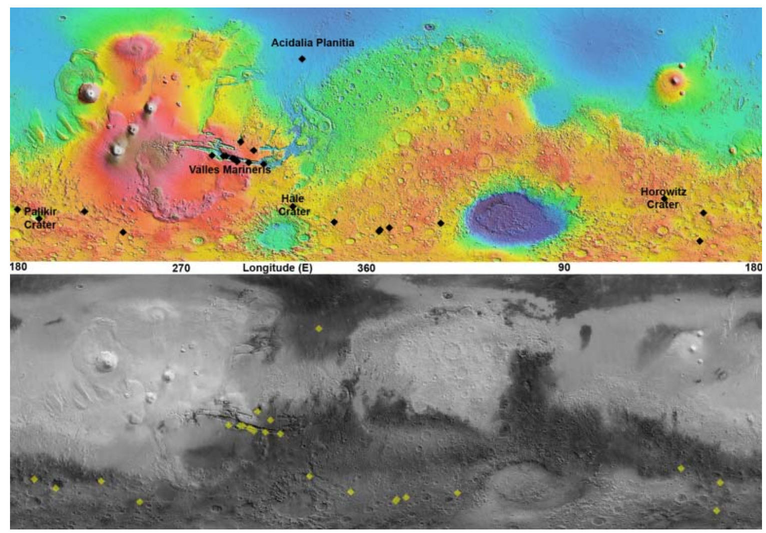
Water Resources


Ice and frost in 35 km diameter crater at 70°N

- High Latitudes (60° - 80° latitude)
  - Region largely covered by seasonal caps during winter season
  - As seasonal caps retreat in spring, frost outliers (both CO_2 and H_2O) are left behind
  - Region surrounding north polar cap largely comprises the Vastitas Borealis Formation, interpreted as composed of ice-rich fine-grained (dust) deposits and ice-rich sediments from ancient fluvial activity.
  - Ice-rich fine-grained deposits also seen surrounding south polar cap, but much thinner than in north.
  - Geomorphic features in this region suggest ice-rich flow associated with glacial activity both today and in past
  - New fresh impacts in this region expose ice excavated from depths ranging from 0.3 m to 1.7 m.
  - Not considered to be Special Regions unless heated to melting
  - Accessibility Limitations: Same as polar caps

Water Resources

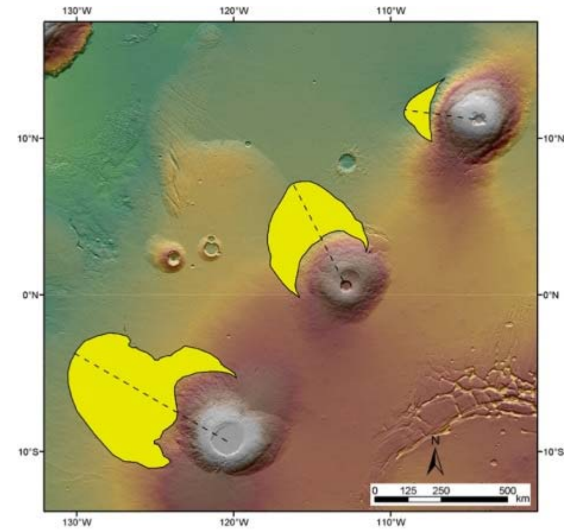
- Mid-Latitudes (30°-60° latitude)
  - Geomorphic evidence of ice-related features emplaced during period of high axial tilt.
  - Geomorphic evidence of features produced by possible fluvial activity in past (gullies, layered deposits in craters, etc.)
  - Recurrent Slope Lineae (RSL) activity concentrated in this zone, particularly in southern hemisphere.
  - Fresh impacts expose ice excavated from 0.3-2.0 meters depth.
  - Region where ice deposition can occur during periods of high axial tilt
  - RSL sites are treated as Special Regions. Other regions in this zone not considered to be Special unless heated to melting or some future observation points to the natural presence of water.
  - Accessibility limitations: Energy produced by solar power limited to summer season



Distribution of confirmed RSLs.

Water Resources

- Equatorial Region (between 30°S and 30°N)
  - RSL sites and potential active gullies suggest presence of near-surface liquid in certain locations.
  - Ice deposits from past periods of high axial tilt remain at depth (>15 m) in localized regions, such as northwest of the Tharsis volcanoes.
  - Areas of H_2O enhancement (from Mars Odyssey neutron analysis) within equatorial region are usually interpreted as being due to hydrated minerals, which may contain water contents up to ~13%.
  - Impact crater analysis, radar data, and neutron spectrometer data suggest that subsurface ice is generally located at depths >5 m in this region and often >50 m depth.
  - RSL sites and possibly the active gullies are Special Regions. Other locations are not Special.
  - Accessibility limitations: High levels of solar energy and warmest temperatures on the planet, but limited accessibility to H_2O.



Tropical glacier deposits along Tharsis volcanoes